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Residential Wood Combustion Study. Task 5
Emissions Testing of Wood Stoves
Volumes 1 and 2

Green (Del) Associates, Inc., Woodburn, OR

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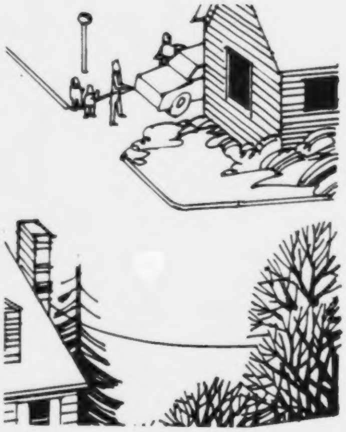
Task 5

Emissions Testing of Wood Stoves
Volumes 1 & 2



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This report presents the results of 19 emission tests on four wood stoves and two retrofit emission control devices. the testing was conducted during June-October 1981. The objectives of this study were to further identify the effect of wood moisture on stove emissions, to evaluate several inexpensive (simplified) test procedures for assessing particulate emissions, and to define a level of particulate emissions which can be expected from state-of-the-art improved combustion stoves. This study included evaluating previous test data reported in the literature.

A single standard operating procedure was used throughout the test program, the objective of which was to maintain a constant heat output rate, as monitored by combustion chamber temperature and stove surface temperature. A heat output rate corresponding to a relatively moderate to low burn rate (less than 2.5 kg wood/hour) was chosen. A single wood type (Douglas fir) was used throughout the study, wood size was maintained at a consistent level. Throughout the entire test program measurements were made for particulates, carbon monoxide, carbon dioxide, oxygen, and hydrocarbon content of the emissions; the gaseous constituents were monitored continuously. Measurements were made for creosote deposition, opacity, and smoke spot density. Appendices for this report are contained in Report No. EPA 910/9-82-089h.

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RESIDENTIAL WOOD COMBUSTION STUDY

TASK 5

EMISSION TESTING OF WOOD STOVES

VOLUMES 1 & 2

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EPA 910/9-82-089a	Residential Wood Combustion Study Task 1 - Ambient Air Quality Impact Analysis
EPA 910/9-82-089b	Task 1 - Appendices
EPA 910/9-82-089c	Task 2A - Current & Projected Air Quality Impacts
EPA 910/9-82-089d	Task 2B - Household Information Survey
EPA 910/9-82-089e	Task 3 - Wood Fuel Use Projection
EPA 910/9-82-089f	Task 4 - Technical Analysis of Wood Stoves
EPA 910/9-82-089g	Task 5 - Emissions Testing of Wood Stoves Volumes 1 & 2
EPA 910/9-82-089h	Task 5 - Emissions Testing of Wood Stoves Volumes 3 & 4 (Appendices)
EPA 910/9-82-089i	Task 6 - Control Strategy Analysis
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RESIDENTIAL WOOD COMBUSTION STUDY

TASK 5

EMISSIONS TESTING OF WOOD STOVES

Volume 1 of 4

RESIDENTIAL WOOD COMBUSTION STUDY

TASK 5

EMISSIONS TESTING OF WOOD STOVES

FINAL REPORT

PREPARED BY:

DEL GREEN ASSOCIATES, INC.
Environmental Technology Division
1535 N. Pacific Highway
Woodburn, Oregon 97071

PREPARED FOR:

U.S. ENVIRONMENTAL PROTECTION AGENCY
Region X
1200 Sixth Avenue
Seattle, Washington 98101

TASK MANAGER

Wayne Grotheer

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12

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INTRODUCTION

Emission testing studies of wood stoves have yielded results indicating a wide range of emission levels. The particulate emissions measured range from approximately 2 grams per kilogram of wood burned for advanced state-of-the-art devices to 75 grams per kilogram of wood burned for the common airtight box stove. However, variations in the measured emission rates can be attributed to more than stove design. Previous studies have indicated that fuel moisture and size, as well as operating procedures (e.g., burn rate) may have a significant impact on emissions. Another extremely important factor affecting the measured emission rates is the test procedure used in determining the particulate emissions; variations in test procedures can result in significant differences in measured emission rates.

This particular study was undertaken with several objectives in mind. The three major objectives of this study were to further identify the effect of wood moisture on stove emissions, to evaluate several inexpensive (simplified) test procedures for assessing particulate emissions, and to define a level of particulate emissions which can be expected from state-of-the-art improved combustion stoves. In order to achieve these objectives, this study included conducting a series of emissions tests, as well as evaluating previous test data reported in the literature.

The emissions tests were conducted in conjunction with OMNI Environmental Services, Portland, Oregon. All tests were conducted at the OMNI facilities under laboratory conditions. These tests were conducted during the period June to October 1981. The test program involved 19 emissions tests with four stoves and two retrofit devices.

In order to try to eliminate the variation in emissions due to operating procedure, a single standard operating procedure was decided upon and used throughout the test program. The objective of this chosen operating procedure was to maintain a constant heat output rate, as monitored by combustion chamber temperature and stove surface temperature. A heat output rate corresponding to a relatively moderate to low burn rate (less than 2.5 kg wood/hour) was desired since it is believed that is typical of wood stove use in the Pacific Northwest where moderate winter temperatures (40 to 50 F) prevail. A single wood type (Douglas fir) was used throughout the study; wood size was maintained at a consistent level.

The test program began with a series of six emission tests conducted on an airtight box stove to evaluate the effect of wood moisture on stove emissions. (Table 2 of the Summary and Conclusions section summarizes the operating parameters for all tests.) During this test series burns were conducted with wood at three different moisture levels (15,25, and greater than 40 percent moisture on a dry basis).

In addition to the moisture test series on the airtight box stoves, three improved technology stoves and two add-on devices were chosen for evaluation during this study in order to determine the effectiveness of state-of-the-art technology in reducing stove emissions. A primary objective of this phase of the study was to determine a reasonable and achievable emission standard. Prior to the testing, the literature was reviewed in order to identify stoves to be evaluated. Three areas of technology were identified and one stove was chosen from each general design area. These areas are catalytic stoves, modified combustion (e.g., secondary, downdraft), and combined technology. The three stoves studied were chosen based on their expected potential for reducing emissions.

In addition, two retrofit devices to be used in conjunction with the airtight box stove were chosen for testing to determine their potential for reducing emissions from existing stoves. The stoves chosen for evaluation included a catalytic stove, a catalytic-modified air path stove, and a ceramic stove; both a catalytic and non-catalytic retrofit device were tested.

Throughout the entire test program measurements were made for particulate, carbon monoxide, carbon dioxide, oxygen, and hydrocarbon content of the emissions; the gaseous constituents were monitored continuously throughout the test burn. In addition, measurements were made for creosote deposition, opacity, and smoke spot density. Particulate emissions were measured using an EPA Method 5 Sampling Train modified to collect condensible organics by including an unheated back-half filter after the third impinger of the impinger train. Consequently, particulate emissions were determined and are reported as both total particulate (front-half filter with condensible fraction) and non-volatile particulate (front-half catch only).

SUMMARY AND CONCLUSIONS

Pertinent results regarding the impact of fuel moisture content on emissions was obtained; test results indicate "medium" moisture wood is likely to yield the lowest emissions. Similarly, useful information regarding the applicability of simplified test procedures was obtained although more data should be collected before coming to any firm conclusions; continuous carbon monoxide and hydrocarbon measurements show the greatest potential as useful simplified procedures. Finally, although a great deal of information was obtained directly from the data on the testing of the innovative technology stoves, performance of these appliances was disappointing; generally results similar to typical well operated units were obtained. Consequently, a "reasonable emission standard" based on these test data would reflect an emission level currently achievable by typical well operated units. Lower emission results (in the range obtained by the ceramic stove during this study) are expected to be achievable, although emission data is not available yet to indicate an appliance can consistently meet these low emission levels at low burn rates (heat output).

Further discussion summarizing the results obtained for each of the project objectives is presented in this section of the report. A summary of recommendations for further work also is provided.

RESULTS

Table 1 summarizes the emissions results from the 19 test runs conducted during this test program. Similarly, Table 2 summarizes the important operating parameters for the appliances during the emission testing.

The tests were conducted at an average burn rate of 2.5 kg/hr, dry basis, (5.5 lb/hr). During the tests the stove surface temperature averaged in the 350 - 400° F range, the combustion chamber temperature averaged 500 - 600° F, and the stack effluent temperature averaged 250 - 300° F.

The average total particulate emission rate for these tests (excluding fuel moisture and cold start emissions tests) was 19 g/kg. Front-half (filterable) particulate emissions averaged 21% of the total with an average filterable emission rate of 3.5 g/kg. The highest emission rate measured was 62 g/kg (11 g/kg, filterable) at a burn rate of 2.7 kg/hr in the air-tight box stove fueled on dry (14%) wood. The lowest particulate emissions obtained, 2 g/kg (1 g/kg filterable) were from the Ceramic stove. However, this stove operated at a significantly higher burn rate (3.9 kg/hr) than did the other appliances and burn rate is known to affect emission levels.

Carbon monoxide and hydrocarbon emissions averaged 115 and 8.7 g/kg, respectively. Creosote deposition averaged 330 mg/m^2 kg. Average opacities measured by the visible emissions observer and transmissometer were 21 and 18 percent, respectively.

The test results are discussed in more detail in the Discussion of Results section of this report.

TABLE 1

Emissions Summary

Test Run	STOVE TYPE	Burn Rate	Particulate Emissions				Creosote[6]	Carbon Monoxide	Gaseous HC	Opacity[8]	Stack Gas Flow	Excess Air
			Total[2]			Front Half[3]						
		kg/hr (lb/hr)[1]	g/dscm	lb/hr	g/kg[4]	g/kg[4] (%)[5]	mg/m^2-kg	g/kg[4]	g/kg[4,7]	%	SCHM (DSCM)	%
1	Box	1.9 (4.1)	1.3	0.09	22	6.3 (29)	969	190	13.8	36	30 (1060	230
2	Box	2.4 (5.3)	3.4	0.28	54	14 (27)	917	189	16.9	30	38 (1350	160
3	Box	2.1 (4.7)	1.5	0.16	34	11 (33)	218	160	10.5	20	50 (1750	180
4	Box[9]	8.1 (17.8)	3.6	0.72	40	9.6 (24)	216	210	11.9	40	91 (3230	140
5	Box	2.7 (6.0)	5.0	0.37	62	11 (17)	592	220	12.1	37	34 (1200	180
6	Box[9]	5.8 (12.8)	3.8	0.54	42	8.3 (20)	291	170	9.2	46	66 (2320	140
7	Box	2.9 (6.4)	1.5	0.12	19	4.4 (23)	568	160	8.8	28	36 (1270	170
8	Box[9]	2.0 (4.5)	0.9	0.11	24	6.1 (25)	109	190	11.1	20	55 (1950	410
9	Box	1.7 (3.7)	1.2	0.08	22	4.8 (22)	240	110	6.6	11	32 (1130	320
10	Box/Catalytic Add-on	2.1 (4.6)	1.3	0.10	22	3.7 (17)	223	110	8.0	24	37 (1320	380
11	Box/Catalytic Add-on	2.6 (5.8)	1.3	0.09	17	3.3 (20)	190	90	6.2	16	32 (1130	240
12	Box/Non-Catalytic Add-on	2.4 (5.4)	1.8	0.21	38	7.4 (20)	273	200	11.8	22	54 (1890	320
13	Box/Non-Catalytic Add-on	2.2 (4.9)	1.8	0.17	35	6.1 (17)	337	160	9.3	23	42 (1490	280
14	Catalytic Box	1.7 (3.7)	2.2	0.14	38	5.9 (16)	379	120	10.7	10	30 (1060	140
15	Catalytic Box	2.2 (4.9)	1.5	0.11	23	4.8 (21)	273	50	7.3	10	34 (1200	172
16	Catalytic/Secondary Air	3.0 (6.7)	0.6	0.09	14	3.5 (25)	88	80	3.9	<5	71 (2500	347
17	Catalytic/Secondary Air	2.1 (4.7)	1.2	0.14	30	5.7 (19)	317	150	5.8	13	56 (1960	498
18	Ceramic	6.4 (14.2	0.2	0.02	1	0.63 (63)	56	20	0.4	-0-	52 (1850	63
19	Ceramic	3.9 (8.7)	0.1	0.01	2	0.97 (49)	27	50	0.6	-0-	49 (1720	97

[1] Dry Basis

[2] Oregon DEQ Method 7

[3] EPA Method 5

[4] Mass Emissions per Mass Dry Fuel Consumed

[5] Percent of Total Emissions

[6] Average of two measurements locations

[7] As Hexane

[8] Visual Observer

[9] Cold Start

TABLE 2

Operating Parameters Summary

Test Run	Stove Type	Burn Rate kg/hr (lb/hr)	Fuel Charge		Fuel Moisture[1]	Fuel Consumed[1]	Burn Duration	Temperature	
			Wet	Dry				Combustion Chamber	Stack Gas
			kg	kg	%	kg	Minutes	°F	°F
1	Box	1.9 (4.1)	11.9	9.4	26	8.5	275	513	265
2	Box	2.4 (5.3)	12.5	11.0	14	10.0	250	543	316
3	Box	2.1 (4.7)	15.7	11.4	126	6.5	181	654	342
4	Box[2]	8.1 (17.8	13.5	11.9	14	4.7	35	675	544
5	Box	2.7 (6.0)	11.8	10.4	14	9.5	208	569	299
6	Box[2]	5.8 (12.8	12.4	10.0	24	4.5	46	598	401
7	Box	2.9 (6.4)	12.9	10.3	25	9.5	198	610	372
8	Box[2]	2.0 (4.5	17.3	7.7	126	5.3	155	470	295
9	Box	1.7 (3.7)	12.5	5.5	126	5.2	189	600	361
10	Box/Catalytic Add-on	2.1 (4.6)	14.0	11.4	22	10.5	299	602	290
11	Box/Catalytic Add-on	2.6 (5.8)	12.6	10.2	23	9.4	223	599	353
12	Box/Non-Catalytic Add-on	2.4 (5.4)	14.0	11.3	24	10.5	255	574	265
13	Box/Non-Catalytic Add-on	2.2 (4.9)	13.3	10.8	23	10.0	270	553	251
14	Catalytic Box	1.7 (3.7)	7.6	6.3	21	5.9	209	609	244
15	Catalytic Box	2.2 (4.9)	7.5	6.0	25	5.6	150	815	323
16	Catalytic/Secondary Air	3.0 (6.7	8.0	6.5	24	6.0	120	627	375
17	Catalytic/Secondary Air	2.1 (4.7	8.5	6.8	25	6.3	175	491	230
18	Ceramic	6.4 (14.2	8.7	7.3	21	6.5	61	1519	779
19	Ceramic	3.9 (8.7	8.9	7.1	25	6.5	99	1195	604

[1] Dry Basis $\left(\frac{\text{lb moisture}}{\text{lb wet wood - lb moisture}}\right) \times 100$

[2] Cold Start

FINDINGS AND CONCLUSIONS

The major findings and conclusions resulting from this study are as follows:

- The results of these appliance tests indicate that average stove emissions expected in normal use would be 20 g/kg total particulate and 4 g/kg filterable particulate (condensible excluded). These tests were conducted at an average combustion rate of 2.5 kg/hr which is considered a low to moderate rate. Barnett[1a] reports that research he has conducted in Upstate New York indicates a typical burn rate of only 1.5 kg/hr. Higher emissions generally are produced at lower burn rates; consequently, the 20 g/kg emissions estimate may actually be lower than emissions from installed stoves operating at burn rates of less than 2.5 kg/hr.

- Particulate emission levels are a function of combustion rate with emissions increasing as burn rate decreases. The results obtained during this study compare qualitatively to results previously obtained[1d,1k,10].

- Fuel moisture content does affect emissions. During this study, emissions ($g/10^4$ Btu) increased significantly for both dry wood (200%) and for wet wood (100%) as compared to the medium moisture fuel. Optimum fuel moisture is in the 25-35%, dry basis (20 - 30% wet basis) range.

- Only one of the improved technology stoves tested resulted in any significant reduction in emissions. The emissions from the Ceramic stove were measured at 1-2 g/kg; a reduction of 90% from the average 20 g/kg. However, this emission reduction must be qualified, since the burn rate for this appliance was significantly higher (5.4 vs 2.5 kg/hr) than the other appliances. Nonetheless, the net efficiency measured for this appliance was similar to the other appliances (65%) even though high stack losses were measured. Further testing (heat output rate and efficiency) of this appliance is warranted to monitor and determine the actual heat release rate characteristics of this stove. If the manufacturer's claim that this ceramic unit "stores" the heat generated during the rapid combustion for slow release during the non-burn periods, the operation of this unit in a high burn batch charge manner would achieve the homeowner's goal of steady heat output, as well as a clean burn with few emissions. This appliance would then provide a basis for defining a reasonable emission level for well designed, clean burning units.

- The catalytic devices did not reduce emissions significantly under the operating conditions of these tests. Catalytic operation was considered marginal for these test operating conditions. A literature review indicates mixed results have been obtained with catalytic devices. Two other investigators (Oregon DEQ[1d] and Barnett[7]) also have reported no significant reduction in measured emissions from box catalytic stoves. However, Barnett[7] recently has reported significant reduction (85%) in emissions from a prototype catalytic stove and Shelton[2,3] has reported significant reductions (up to 50%) in creosote from the same catalytic add-on device tested in this study. (Discussed in more detail later in this section). The conclusion from this study is that simple addition of a catalytic device to a standard appliance is not guaranteed to reduce emissions. More testing in this area may be warranted in order to characterize the range of operating parameters which will result in reduced emissions from catalytic appliances. This testing could be conducted by a simplified test procedure (e.g., CO) to determine under what conditions adequate catalytic combustion is achieved.

- The Catalytic Modified Combustion appliance did not result in significantly lower emissions than the norm, although this appliance when operating properly did have an emission rate at the lower end of the normal range (14 g/kg).

- The non-catalytic add-on device did not reduce emission levels under the test conditions of this study. However, two other investigations (Oregon DEQ[1d] and Shelton[3]) found emission reductions of 50 and 21%, respectively for this device. (Shelton's work was for creosote deposition).

- Test results obtained confirmed the importance of operating conditions in obtaining meaningful results. As previously noted, a correlation between burn rate and emissions was obtained. Furthermore, for two of the stoves tested (catalytic box and catalytic modified combustion), a significant difference in emission rates (50% reduction) was noted for the two runs in each of the paired samples and it is believed these significant differences were directly related to operating changes (i.e., burn rate and combustion chamber temperature), and not simply to measurement error.

- Due to the generally poor performance of the improved technology appliances, these test data do not provide a good basis for establishing a technology forcing Emission Standard. Strictly based on these test data, a standard of 15-20 g/kg (5-10 g/kg filterable) would be justifiable. Nonetheless, the results of the ceramic stove tests (at an elevated burn rate), as well as other data from the literature (Barnett's[7] catalytic protype, Oregon DEQ[1d] results on a furnace) suggest that an emission rate of 5 g/kg (1 g/kg filterable) at a typically used burn rate (1.0 - 2.5 kg/hr) may ultimately be achievable in a well designed appliance. Construction of smaller stoves to be operated at low burn rates more typical of normal home use may help to achieve this goal.

- The correlation between total particulate matter and several "simplified" procedures -- creosote, carbon monoxide, hydrocarbons, opacity, and smoke spot density -- were all examined. Results of these correlations were:
    - A reasonable correlation (correlation coefficient 0.8) with particulate matter was obtained for carbon monoxide and hydrocarbons (adjusted for excess air). Either of these parameters could be used to monitor and characterize particulate emissions levels. Additional data would definitely need to be collected prior to using such a correlation for actually certifying appliance emissions rates, should a certification program be initiated.
    - A correlation between particulate matter and creosote was established. A correlation coefficient of 0.80 was obtained (two data points deleted). However, multiple creosote samples were collected during this study and relatively poor precision among samples was obtained (correlation coefficient of 0.6 between samples at two different locations during same test). Another investigator (Barnett[7]) has reported "excellent" correlation between coreosote and particulate. However this correlation was based on average values, and as in this study, all tests were conducted under similar stove operating conditions. The results of a recent (February 1982) study[2,3] by Shelton cast serious doubt on the utility of creosote deposition as a general simplified method for estimating emission rates. In his study Shelton showed that creosote deposition was decreased by 75% by use of a stack barametric damper; basically, the reduction was due to the effect of dilution air and increased flue gas flow, and no corresponding reduction in actual emissions to the atmosphere would be expected.
    - A correlation was obtained between particulate matter and opacity with a correlation coefficient of 0.8. However, this correlation is for particulate matter concentration (g/dscm). This has limited benefit as a simplified test method since concentration will be affected by excess air. Any increase in excess air will result in a decreased opacity level. Consequently, opacity may not be an accurate indication of total emissions. Nonetheless, opacity could be used as a screening device to indicate emission levels known to exceed a particular level. In other words, if opacity exceeded a given level, one could be assured the emissions exceeded a corresponding level (g/kg); however, if the opacity was less than a given level, one could not be certain the emissions did not exceed a

corresponding level (g/kg) because of the potential effect of dilution (excess) air on the particulate concentration. (High type II error -- false acceptance.)

  - No correlation was obtained between particulate emissions and smoke spot density; the method was not sensitive enough to measure corresponding changes in emissions.

- Filterable (Method 5 Front-half) particulate averaged 21% of the total particulate catch. This percentage was fairly constant except for the ceramic stove which had significantly less total emissions; in this case the filterable fraction was a higher percentage of the total. This simply indicates that improved combustion has a greater impact on the condensible fraction than on the filterable fraction. Nonetheless, filterable particulate could be used as a test method for establishing emission levels; use of this method would simply narrow the emission range (total particulate range of 1 to 62 g/kg versus filterable range of 0.6 to 14 g/kg). Since a great deal of the emissions reduction occurs in the condensible fraction, use of a filterable only method would result in a slight penalty to the low emitting units when comparing emissions. For example, based on total particulate, the ceramic stove indicates a reduction of 90% from the average emission value (2 vs 20 g/kg), but only a 75% emission reduction for filterable particulate (1 vs 4 g/kg)

- No trend was apparent from these data (3 tests only) to indicate the effect on emissions of a cold start as compared to a start from a hot bed of coals.

DISCUSSION OF MAJOR FINDINGS

The major findings relative to the three major objectives of this study -- effect of fuel moisture content on emissions, evaluation of simplified test procedures, and evaluation of innovative appliances to define Reasonable Emission Levels are discussed in more detail below. The author intentionally has avoided providing a great deal of data and data analysis in this section. The reader is referred to the Discussion of Results section of this report for evaluation of the actual data and information obtained from the literature review.

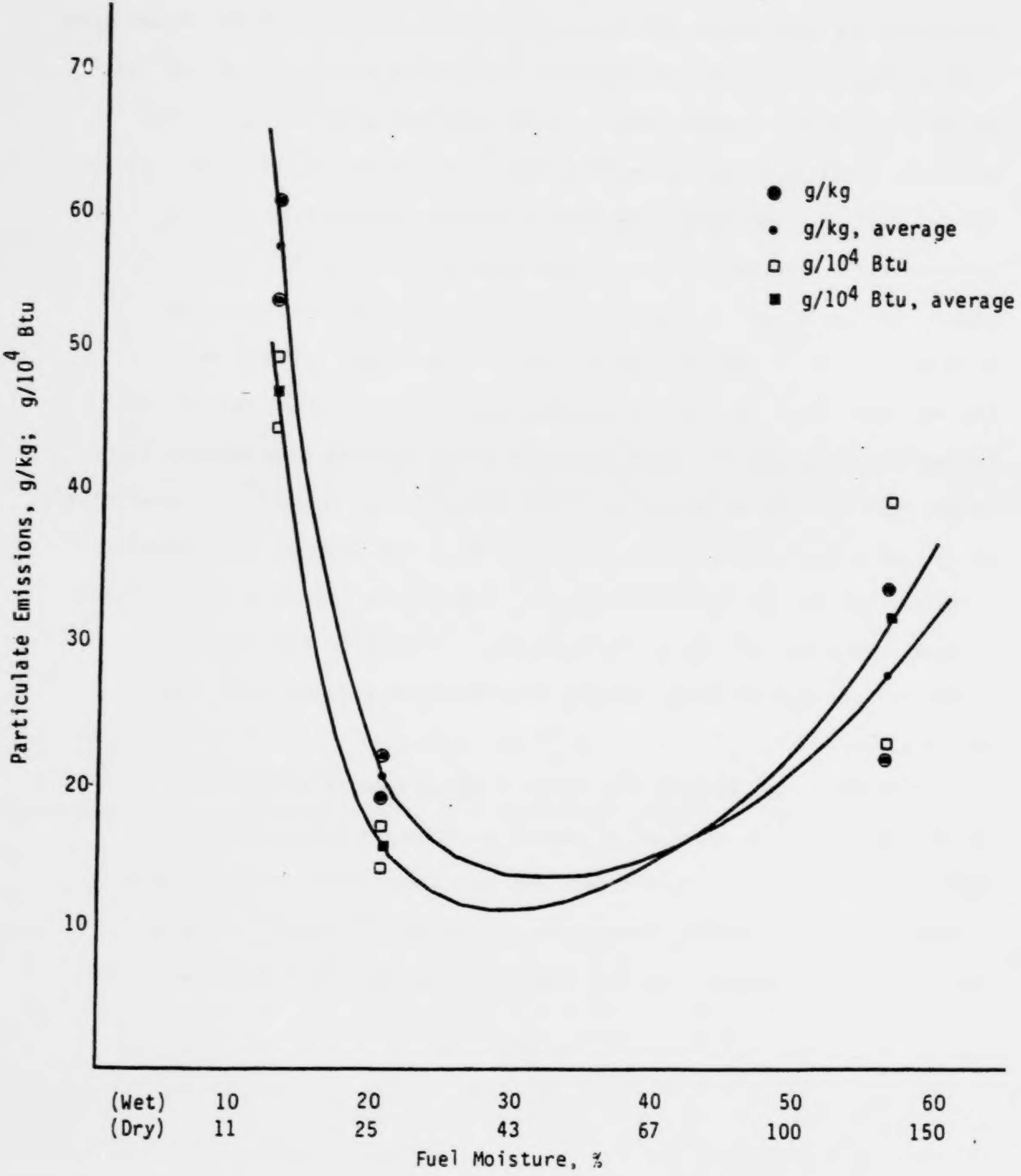
Effect of Fuel Moisture on Emissions

The results of this study indicate particulate emissions are significantly affected by wood fuel moisture. Figure 1 graphically presents the results obtained. Based on these tests the optimum fuel moisture range is 25-35 percent, dry basis. It is important to note that the results presented are results obtained with the appliances operating at nearly the same combustion rate. This is important in interpreting the results since emissions have been shown to be dependent upon combustion rate. Consequently, the high emissions obtained with the dry fuel are expected to be largely due to the fact that the air inlet was restricted during these tests in order to maintain a heat output rate consistant with the medium moisture tests. This operation is considered typical of how a homeowner would operate an appliance, since the ultimate objective of a user generally is a constant heat output.

The results obtained during this study mostly are consistent with results obtained by Shelton[6,8] during two studies (comparison of results is discussed in more detail in the discussion of Results section). In one

FIGURE 1

Particulate Emissions As A Function
of
Fuel Moisture



study[6] Shelton measured efficiency as a function of fuel moisture (emissions were not actually measured). Based on this study by Shelton (assuming emissions to be inversely proportional to combustion efficiency) one would expect minimum emissions to occur in the 25-35% moisture range with emissions increasing for both higher and lower moisture levels. In Sheltons second study[8], creosote accumulation was measured as a function of fuel moisture; the results of the study indicate decreasing creosote emissions with increasing fuel moisture. Shelton's results confirm that higher emissions are to be expected for dry fuel, but contradict the results obtained during this study for high moisture fuel. However, burn rate data were not provided for Shelton's study. Shelton's general approach was to maintain constant heat output. Consequently, it is assumed that a slightly higher burn rate was used for the wet fuel tests in order to maintain the same heat output rate as the medium fuel tests (an increased burn rate being required to compensate for a latent heat loss due to moisture). This assumption is unconfirmed; nonetheless, an increased burn rate would account for some of the apparent reduction in emissions for the wet fuel. Furthermore, creosote may not be a true indicator of total emissions emitted to the atmosphere, especially when operating conditions are significantly changed (fuel moisture content, fuel type, excess air).

In summary, the optimum fuel moisture range appears to be 25-35% dry basis. Dryer fuel is expected to result in increased emissions. The emissions expected for very wet fuel are less clear; this study indicates slightly greater emissions, whereas one of Shelton's[8] studies indicates less emissions. However, the fact that more fuel must be consumed when wet fuel is used (due to the heat loss from vaporization of water) warrants using properly seasoned wood, even if no emission reduction can be confirmed.

Evaluation of Simplified Test Procedures

Of the five simplified test procedures evaluated during this study, carbon monoxide (CO) and/or total hydrocarbon (THC) measurements offer the greatest advantages and flexibility. For both CO and THC a correlation coefficient of 0.8 was obtained between concentration (adjusted for excess air) and total particulate matter. One of the advantages of this procedure is that if concentration of the gaseous pollutant correlates with measured total particulate (g/kg) than stack gas volumetric flow rate does not need to be measured. Another advantage of measurement of CO concentration is that cost and level of effort can be adjusted depending upon the level of accuracy required. Different techniques (varying from orsat to laboratory quality continuous monitoring instrumentation) can be used for the measurements. For example, the cost of using this method to evaluate a single burn cycle is estimated at between $300 and $600 depending upon whether an orsat method or instrumental technique is used, with a corresponding capital cost range of $600 to $13,000. Comparable estimated costs for conducting a single Method 5 test are $2,100 (level of effort) and $20,000 (initial capital expenditure). Further study should be conducted and additional data obtained to verify the correlation of CO and THC to total particulate and to examine use of the method over a wider range of conditions.

Creosote deposition measurements are extremely inexpensive, requiring almost no capital expenditure and very little level of effort.

The test can be conducted for as long or as short a period of time as desired with little additional cost or level of effort over that required for operation of the appliance. However, the results obtained during this study, as well as information obtained from the literature review indicate that problems may exist with precision of the technique and with the range of conditions for which it may apply. These problems are discussed in more detail in the Discussion of Results section.

The usefulness of opacity measurements is limited to that of a screening technique, due to the techniques dependence upon excess air dilution. As mentioned earlier in this summary, evaluation of the smoke spot density data did not result in any apparent correlation.

One simplified technique, high volume sampling, not evaluated in this study due to budgetary constraints, warrants investigation. There is no real cost benefit to using this method. The advantage of this method as a simplified technique is that the sampling period is extremely short which permits discreet samples to be taken during various periods of the burn cycle. This is useful for evaluating changes in stove performance as operating conditions are changed. A comparative test series of this method with EPA Method 5 would provide the data necessary to determine how the filterable particulate measured by the High Volume method compares to the total particulate measured by EPA Method 5. Table 48 in the Discussion of Results section summarizes the advantages, disadvantages, and costs of the simplified methods evaluated during this study.

Evaluation of Innovative Technology Appliances to Define Reasonable Emission Levels

Of the three innovative technology appliances and two retrofit devices tested during this study, only one appliance -- the ceramic stove -- resulted in significant emissions reduction (90%) from the baseline level established from a typical box (step-type) stove operating at similar conditions. However, due to the high burn rate of this appliance, the meaningfulness of the low emission rate obtained (1-2 g/kg) is somewhat obscured. Further testing of this appliance's heat output rate characteristics is warranted to determine if the unit will provide a steady heat output (due to storage capabilities of the ceramic) even when operated in a high burn -- batch type firing mode.

A literature review was conducted. Average emissions reported by various researchers for tests conducted at burn rates of less than 3.5 kg/hr are as follows (these data are presented and discussed in more detail in the Discussion of Results section):

Investigator	Total Particulate g/kg[a]	Filterable Particulate g/kg[a]
DGA/OMNI	27	6
Oregon DEQ[1d]	32[c]	15[c]
Sanborn[1h]	27	18
Barnett[1a,7]	-	7[b]
Butcher[10] (1979)	-	9[b]
Butcher[1k] (1980)	-	4[b]

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[a] Dry basis

[b] High volume

[c] Includes results from tests with burn rate up to 4.5 g/kg

Total particulate is defined as the combined filterable (front-half) and condensible fraction of the EPA Method 5 sampling system (with or without modification to include second back-up filter after impinger train). Filterable particulate is the front-half filter catch of the Method 5 sampling system, or the particulate matter collected by an unheated filter of a high volume sampling system (with or without dilution air added prior to contact with the filter). These data indicate an average emission rate of greater than 25 g/kg.

Results from this study (e.g., results of catalytic-modified combustion unit when operated at proper combustion temperature) indicate an emission level of from 15-20 g/kg total particulate (5-10 g/kg filterable) is reasonable to expect from well operated commercial units currently available. Limited data from several tests indicate that emissions levels as low as 5 g/kg (1 g/kg filterable) from improved technology appliances are achievable but not necessarily at the low burn rates typically used in small home appliances; such a low emission level should be considered "technology forcing" at this time. The limited data are:

Appliance	# Tests	Burn Rate kg/hr	Total Part. g/kg	Filterable Part. g/kg
Ceramic Stove	2	5	2	1
Furnace[1d]	2	14	4	1
Catalytic Appliance[7]	3	1.6	-	1

Although no significant emissions reductions were noted for the two retrofit devices (catalytic and non-catalytic) tested during this study, Shelton's[2,3] recent results indicate a reduction in creosote deposition of up to 20% for the same non-catalytic device and up to 50% for the same catalytic device. Oregon DEQ[1d] noted an emissions reduction of 50% for the non-catalytic device during their study (1 test run only). The disparity in results for the catalytic device indicates that a reduction in emissions from catalytic action can not be automatically assumed; instead, like emissions reduction achieved from other combustion techniques reduction of emissions from catalytic action are critically dependent upon numerous operating conditions. Factors which affect catalytic action include flue gas temperatures, oxygen available, residence time at the catalyst, and the proper mixing of effluent gases and combustion air. To what degree the conditions necessary for emissions reduction by catalytic action are dependent upon appliance design, appliance operating conditions, and/or operator actions is unclear at this point. Proper catalytic action is no doubt a function of all these, but the limiting factors have yet to be clearly defined.

In any event, Shelton's results indicate a reduction of up to 50% (based on creosote deposition) may be achievable from retrofit devices (note that the non-catalytic device costs about $150 and the catalytic unit about $300). This level of emission reduction would likely result in average emissions in the 15-20 g/kg range for existing units.

The effect of test methods and appliance operation -- especially appliance operation -- on measured emissions is significant. Consequently, it must be understood that in defining any emissions level certain parameters regarding these two variables also must be defined and subsequently go hand-in-hand with the defined emission level. For this discussion of emission levels, the author has basically assumed the appliance is operated at a combustion rate of less than 3 kg/hr, and that emissions are measured by EPA Method 5 with condensible analysis. For any emissions measurement program to determine or compare emissions from various appliances (whether for certification or research) stove operating procedures and test methods must be carefully defined if the results are to be meaningful. Development of such a standard test protocol is well outside the scope of this project.

RECOMMENDATIONS FOR FURTHER STUDY

The results obtained during this study indicate the need for further study of various items related to wood stove emissions and the measurement of wood stove emissions. Recommendations for further study are summarized below:

- A standard operating/test protocol by which to compare stove emissions is required. Considerable effort will be required to develop such a protocol, but considering the impact operating conditions have on emission rates, the effort is necessary. The protocol should include requirements for testing at two or three (low, medium and possibly high) heat output rates and should establish a specific criterion for fuel load/stove volume. Other details such as fuel moisture, fuel type, fuel size, and stove operating cycle (when to start and stop emission test) must also be addressed. Obviously, specific emission test methods criteria also must be established.

- Evaluation of "typical" burn rates actually used in the Pacific Northwest is suggested. Due to the significant dependence of emissions on burn rate, it would prove profitable to conduct a study to determine the actual combustion rates (heat release rate) normally used by homeowners in the Pacific Northwest. This information can be used to better estimate emission factors from existing installations, to determine the rates at which stoves should be operated during emission testing, and to determine proper stove sizing for the "typical" Northwest installation.

- Techniques for measuring low velocity flow rates during stove emission testing should be evaluated with the goal of establishing an acceptable standard procedure. Development of a low flow measurement technique will not only provide an independent technique for determining mass flow which can be used to validate stoichiometric mass balance, but also will provide the basis required for conducting proportional sampling (particulate sampling rate proportional to volumetric flow rate).

- Conduct additional testing to verify the correlation of CO and THC to total particulate and to examine the use of this simplified method over a wider range of operating/emission conditions.

- Conduct additional testing to further evaluate the potential of creosote measurements as a simplified test procedure. A two-fold evaluation is recommended. First, evaluate the precision of the method by conducting a series of tests using simultaneous multiple creosote measurements, and refine the method as necessary. If adequate precision is obtained, then evaluate the creosote technique in relation to the standard particulate measurement technique (EPA Method 5 with back-half analysis).

- Conduct a controlled comparative study of the emissions measured by EPA Method 5 and a high volume sampling technique. This evaluation would give a basis of comparison for the emissions data already collected by the different methods, and would also help to define the potential of the high volume method as a "simplified" emissions measurement technique.

- Conduct additional testing of catalytic stoves and develop a "screening" protocol for catalytic operation. Conflicting results have been obtained regarding the ability of catalytic devices to reduce emissions from wood stoves; however, the potential for emissions reduction warrants further study of catalytic systems. Combustion conditions (therefore stove operating conditions) are extremely important to proper catalyst operation. Consequently, an important aspect of any study of catalytic appliances is the establishment of proper operating procedures and conditions. A screening protocol should be developed (e.g., use of CO/HC monitoring) to use in identifying catalytic stove operating boundaries prior to emission testing.

- Additional testing to determine the actual instantaneous heat release characteristics of the ceramic stove should be considered. Any additional testing should include a detailed evaluation of the stoves heat output rate and efficiency while operated in a batch type operation (i.e., initial fuel load with high burn rate followed by waiting period prior to recharging).

EXPERIMENTAL APPROACH

STOVE OPERATION

Of major consideration during any wood stove test program is determination of the stove operating procedures to be followed during the emission testing. Two basic approaches are available. In the first case, stove damper and inlet air settings are established at the beginning of a test burn, and no adjustments are made throughout the burn. For this case, one might suspect that run to run variations would be reduced. In the second case, stove operating parameters (e.g., combustion chamber temperature, excess air, etc.) are monitored during the burn and adjustments are made to the air inlets and/or draft in order to maintain the monitored parameter within a certain range. In this study, the latter approach was followed. The parameters to be monitored were combustion chamber temperature and stove skin temperature.

Of primary consideration in establishing the operating parameters for this test series was how the typical Pacific Northwest homeowner would normally operate a stove. Due to the moderate climate in the Pacific Northwest, a low to medium burn rate was desired - certainly not a high burn rate. A typical homeowner would make adjustments to stove operation based on heat output. That is, a homeowner would not adjust the stove damper based on stack temperature, emissions, or even burn rate, but instead would make adjustments depending upon whether more or less heat is desired from the stove. Therefore, the test protocol established a desire to maintain a constant heat output. Unfortunately, this parameter is not easily monitored. Consequently, the objective of our operating technique was to obtain and maintain a near constant combustion chamber temperature (500°F) and stove surface temperature (350-400°F). Obviously, the stove surface temperature reacts slowly to changes in combustion rate. Therefore, although both parameters were continuously monitored, the combustion chamber temperature was generally the parameter used to determine whether or not air inlet and damper adjustments were required.

Prior to conducting any emission tests, experimental burns were conducted with the airtight stove to determine the basic operating procedure to be followed and to establish draft settings and burn rate. After several tests an operating procedure was determined which resulted in a combustion chamber temperature of 500° F, a stove surface temperature of 350 - 400 °F, and a burn rate of 2.5 kg/hr. These ranges for combustion chamber and stove surface temperatures then became the guidelines for the rest of the test program. However, it must be noted that this combustion chamber temperature is marginal in regards to the required temperatures for operation of the catalytic stoves. During testing of the catalytic stoves, care was taken to assure that an adequate "light-off" temperature (normally 1000 ° F) was reached and an attempt was made to maintain the combustion chamber temperature (e.g., the temperature of the gas stream feeding the catalyst) at a level above the manufacturer's suggested minimum temperature for maintaining catalytic reaction.

All emission tests were conducted on a single charge of wood fed to a hot bed of coals. The normal procedure followed was to first charge the stove with a known mass of wood to bring the stove surface temperature up to the desired level and to establish the hot coal bed. Once this initial charge was reduced to less than one-tenth its initial weight (dry basis), the stove was ready for the test burn charge. After taring the stove scale, a weighed amount of kindling and wood was loaded to the stove and the emission test was begun. The doors remained open for 30 seconds to 3 minutes until it could be determined that the fire was well established. The doors were closed and the air control dampers were opened (usually full open at the very beginning of the burn). Once the combustion temperature reached the appropriate level, the dampers were regulated to a partially closed position; monitoring of the combustion chamber temperature continued throughout the test run. The test burn and emission testing was considered complete when less than 10% of the wood mass charged (dry basis) remained. During the burn, the stove generally was opened once near the end of the burn, primarily to redistribute the wood into a single pile in the chamber.

WOOD TYPE

All tests were conducted using split Douglas fir as the fuel. Where bark was present, the bark was not removed. The size of the pieces generally was in the 12 - 16 inch (girth) range. With the exception of the high moisture test runs, the wood was seasoned; the high moisture test runs were conducted with freshly cut, green Douglas fir.

Prior to each test run, moisture measurements were made on each piece of wood to be used for that burn. These moisture values were recorded and the average moisture value determined. The actual procedure used for wood moisture determination is discussed later in the Sampling and Analytical Procedures Section.

TEST PROTOCOL

Moisture Tests

The purpose of this test series was to determine the impact of wood moisture content on emissions. The series of tests conducted consisted of six test burns using the airtight box stove. Two burns were conducted at each of three moisture levels[a]; low (15-20 percent), medium (25-30 percent), and high (greater than 40 percent). The test protocol for this test series called for conducting all tests under the same stove operating conditions, as discussed in a previous section of this report. Consequently, instead of operating the stove with the same damper/air settings for each moisture content; the air settings were adjusted in order to achieve similar stove skin temperatures, combustion chamber temperatures, and consequently, burn rate.

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[a] dry basis

During this series of tests three of the emission samples (one for each wood moisture level) were "split" samples. That is, Method 5 particulate sampling trains were changed during the run so that emission rates from different parts (phases) of the burn could be independently determined. Furthermore, three "cold start" tests also were conducted as part of this test series. The cold start tests were short runs conducted on the initial charge of wood to the cold stoves. Emissions measured during start-up a cold stove were to be compared to emissions measured when a fresh fuel load is added to a hot coal bed. Consequently, this phase of the test program actually included 12 emission test for 9 burns.

Reasonable Emission Level

This series of emission tests were conducted in order to determine if improved technology stoves would have a significant impact on reducing wood stove emissions. If a significant reduction in emissions could be measured, then a "reasonable" emission level to be expected from wood stoves could be developed from these data. The test protocol called for sampling three different improved technology stoves, as well as two retrofit devices to be used on existing airtight box stoves. Two test runs on each stove were conducted under the same stove operating conditions. For all test runs, medium (25-30 percent) moisture wood was used as the fuel. Split emission samples were collected during one run for each of the stoves tested. Consequently, a total of 15 emission tests were conducted for 10 test burns.

For the catalytic stoves, the stove operating procedures included the additional criterion of operating the stove at a high enough burn rate to assure a gas temperature sufficient for catalytic oxidation. However, the starting point for determining the burn rate was the same operating conditions (combustion chamber temperature 500°F, and stove surface temperature 350 - 400°F) as with the initial airtight stove tests. Thus, even during the testing for a reasonable emission levels, the stoves were intentionally operated at a moderate to low burn rate.

The burn rate for one stove in this test series (Ceramic) could not be controlled since the manufacturer provides no inlet air adjustments. A damper is provided in the stack, and this damper was placed in the fully closed position during testing.

Simplified Test Procedure

One of the objectives of this project was to evaluate "simplified procedures" for measuring the emissions from wood stoves. The protocol for this phase of the project called for simultaneous sampling using several methods so that the results could be directly compared. This multiple sampling was conducted throughout the test program during the moisture and reasonable emission levels test series. No additional test burns were conducted specifically for this purpose. Test procedures utilized for the simplified sampling included continuous measurement of carbon monoxide, carbon dioxide, oxygen and hydrocarbons; measurement of stack gas opacity; measurement of creosote accummulation; and, a smoke spot density test.

STOVE SELECTION AND DESCRIPTION

A stove typical of those currently in use was desired for testing the impact of wood moisture on emissions. Consequently, a simple airtight box stove was chosen for these tests. Since this stove type is considered representative of stoves currently in use, this stove also was used in conjunction with testing of the retrofit devices. The airtight box stove tested did not include any design features one would expect to reduce emissions (e.g., baffles, secondary combustion, thermostatic damper). Consequently, this stove could be used to establish an emissions baseline for wood stoves operated at the test conditions.

As already mentioned the test protocol called for the testing of "improved" technology stoves to determine if and to what extent emission reductions could be obtained. A literature search of technical papers and manufacturer's information was conducted to identify the stoves to be tested. Initially, several stove design categories were identified and considered likely to result in reduced emissions. These general categories were: downdraft, secondary combustion, catalytic, and design combinations such as catalytic/downdraft.

The final decision on which stoves to test was based on several factors. The factors considered in the selection process were perceived potential for reduced emissions, stove availability in the Pacific Northwest, and results of emission data, where available. Review of the market place did not reveal any true downdraft stoves that were actively being marketed in the Pacific Northwest. Consequently, this stove category was dropped from consideration. Two secondary combustion air units and one ceramic stove were identified as potential candidates. Due to limited resources, only one stove could be tested. Based on discussion with the manufacturers or manufacturer's representatives the decision was made to include the ceramic stove in the test program, since this stove incorporates a unique technology -- combustion at high temperature with (theoretically) storage of the heat in the ceramic for later slow release. Two stoves utilizing catalysts to reduce emissions and increase thermal efficiency were identified and chosen for testing. One stove was typical of the majority of the prototype catalytic stoves just entering the marketplace at the time of this test program. That is, the stove is similar in configuration to the typical airtight box stove but with a ceramic honeycomb structure coated with a catalyst placed just prior to the stove outlet. Some secondary air also is added just prior to the catalyst face in order to assure adequate oxygen is present for combustion. The second catalytic stove tested can be categorized as a catalytic/modified combustion stove because this stove includes features in addition to the catalyst (e.g., tertiary air and baffling) to further enhance the combustion process. This stove was chosen as the combination technology stove.

Two retrofit devices with the potential for reducing emissions (e.g., retrofit devices intended for other than simply increasing heat transfer efficiency) were chosen for testing. Both the devices were designed to reduce emissions after primary combustion as opposed to changing basic stove operating parameters for emissions reduction (e.g., thermostatically controlled barametric dampers). The only catalytic retrofit known to exist on the market was chosen for testing. This device essentially retrofits the typical ceramic honeycomb catalyst structure directly to the stove exit flue. The second device tested retrofits in exactly the same manner, but is non-catalytic; the device consists of a heavy stainless steel pad designed to capture particulate matter as it leaves the stove and retain the material for removal or combustion at a later time.

Although many other stove designs are available and many of those investigated offered potential emission reductions, budget constraints limited the stoves and retrofit devices which could be tested. The design features of the devices chosen for testing are discussed in further detail in the following sections.

SAMPLING AND ANALYTICAL METHODS

General Test Procedure

As already mentioned each test burn was conducted with a single charge of wood of known mass and moisture content. Emission testing was begun as soon as the test charge was ignited and testing was terminated when one-tenth the initial charge mass (dry basis) remained in the chamber. Testing was continuous throughout the run except in several cases where "split" samples were taken. Data have indicated that more emissions may be generated during the initial phase (first hour) of a burn. Since one of the purposes of this test program was to correlate data from several test procedures (e.g., opacity, smoke spot) with particulate mass data, it was desired to take as many distinct particulate samples as possible and preferably to take these measurements at different mass emission rates. Consequently, for several of the test runs, the burn was divided into two phases and separate ("split") emissions samples were taken for each phase. In this case a second sample train was prepared and ready for testing prior to beginning the test burn. At the appropriate time, one sample train was removed and immediately replaced by the second sampler. This entire process took less than five minutes. For these two-phase test burns, the criteria used to determine the beginning of the second phase was when the remaining wood mass equaled less than 75% of the initial charge (dry basis). This generally occurred at about three quarters to one-hour into the burn. Two phase samples were taken for Runs 1, 2, 3, 10, 13, 14, 17, and 19. The following sections briefly describe the test and analytical procedures followed during this test program.

Particulate Measurements

Particulate measurements were conducted according to the procedures of Oregon Source Test Method 7. This method is essentially EPA Test Method 5 except that the sampling train is modified to include an unheated filter between the third and silica gel impingers. As per Method 5, the front filter is maintained at a temperature of 250° F, and the impinger train is maintained in an ice bath. Figure 2 is a schematic of the sampling apparatus. Analysis includes measurement of the condensible fraction collected in the impinger train. As per Oregon Method 7, during this study the following sample fractions were collected and analyzed:

1. Filterable (front half) Particulate

   The filterable particulate is determined by combining two sample fractions.

   a. Acetone rinse of nozzle, probe, and front-half of front filter holder - the wash is evaporated to dryness and the particulate gravimetrically determined.

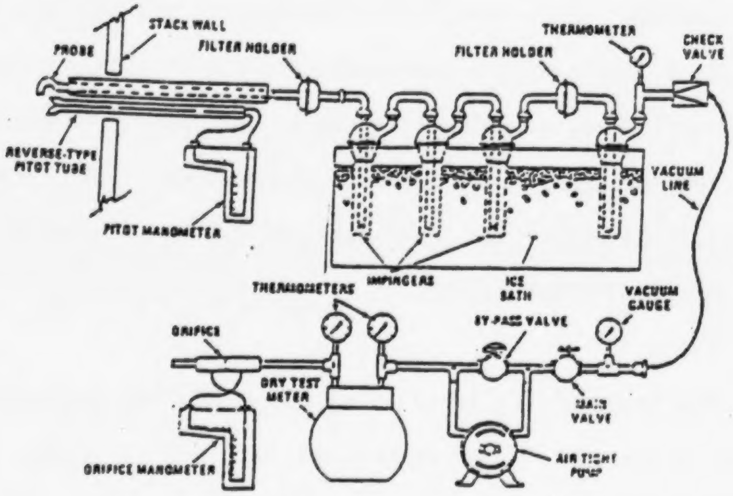
   b. Front filter - the glass fiber filter is desiccated and brought to constant weight to gravimetrically determine particulate.

2. Condensible (back-half) Particulate

   The back-half particulate is determined by analyzing four separate sample fractions.

FIGURE 2

Particulate Sampling Apparatus


STACK WALL
PROBE
FILTER HOLDER
THERMOMETER
CHECK VALVE
FILTER HOLDER
REVERSE-TYPE PITOT TUBE
VACUUM LINE
PITOT MANOMETER
IMPINGERS
ICE BATH
THERMOMETERS
VACUUM GAUGE
ORIFICE
BY-PASS VALVE
DRY TEST METER
MAIN VALVE
AIR TIGHT PUMP
ORIFICE MANOMETER

a. Impinger contents, organic fraction - the contents of the impingers are extracted with dichloromethane (CH_2CL_2, methylene chloride). This extracted organic fraction then is evaporated to dryness and the remaining residue is gravimetrically determined.

b. Impinger contents, water fraction - after extraction of the impinger contents with organic solvent, the remaining water fraction is brought to dryness and the residue gravimetrically determined.

c. Impinger acetone wash - after removing the impinger contents for analysis and completing the distilled water impinger wash (which is added to the impinger contents), the impinger train is rinsed with acetone. This acetone wash is evaporated to dryness and the residue gravimetrically determined.

d. Filter

The back-half filter is desiccated, and the particulate mass is gravimetrically determined.

3. Total Particulate

Total particulate is determined by combining the results of the front-half and back-half analyses.

During this test program, sample recovery was completed at the test site location immediately following completion of the test run. All samples then were sent to the laboratory for analysis.

The only major deviation from the established test method is that single point sampling was conducted throughout the test program. The center of the flue duct was chosen as the sample point. Secondly, although probe nozzle sizes and sampling rates were chosen to approximate isolinetic sampling, isokinetic sampling was not of major concern; a criterion of ±10% isokinetic was not used to determine whether or not a test run was valid.

Stack Volumetric Flow

A calibrated S-type pitot tube was used during the testing to measure the stack gas velocity head. A micromanometer was used in conjunction with this pitot tube due to the extremely low flow rates and, consequently, low pressure differentials. Although the pitot tube was calibrated prior to use, measurements obtained during testing are considered inaccurate. This conclusion was reached based on mass (carbon) balance calculations. This is not surprising since the apparent flow rates measured were very low (2-5 fps) with velocity head pressure differentials in the .001 to .004 inches water range. Even with a micromanometer, measurement of pressure differentials in this range is marginal. Secondly, the small size of the stack (8-inch diameter) can potentially cause an error in velocity measurements due to blockage effects of the probe (the stack area is small enough that the cross-sectional area of the probe is significant and can result in erroneous pressure differential readings); the expected result would be pressure radings biased high.

Consequently, volumetric flow rates were determined using stoichiometric calculations and measured carbon monoxide, carbon dioxide, and gaseous hydrocarbons (as Hexane) concentrations to calculate the total volumetric flow for the entire test period. The average concentrations calculated from measurements (5-minute intervals) by the continuous monitors were used for these calculations. Fuel mass burned was determined from direct measurements of the platform balance and of fuel moisture content.

The assumptions and calculations followed are presented in detail in Appendix A.

Carbon Monoxide, Carbon Dioxide, and Oxygen

Measurement of these gases were conducted by two separate techniques during the sampling. An Orsat was used to measure CO, CO_2, and O_2, periodically during the testing (at half-hour to one-hour intervals). In addition, a non-dispersive infrared (NDIR) analyzer was utilized to continuously monitor the CO and CO_2 content of the effluent; an oxygen analyzer was utilized for continuous oxygen measurement (Runs 10 - 19 only). All instruments were calibrated before and after each test period (e.g., before and after each run or daily when more than one run was conducted in a day).

The sample for all gaseous measurements were taken from the same point in the stack via a single probe and line; the sample line then was split three ways to serve the NDIR, oxygen analyzer, and orsat.

Hydrocarbons

Gaseous hydrocarbons were measured with a NDIR calibrated on hexane. A gaseous sample was continuously taken from the effluent stream and fed to the analyzer. The sample was taken via the same sampling probe and line as the CO, CO_2, and O_2 samples. The analyzer was calibrated on a daily basis using hexane; no attempt was made to determine the analyzer's response to other organic gases.

Opacity

Stack gas opacity measurements were made by two separate procedures throughout the testing program. Visual observations by a certified observer were periodically conducted. Observations were generally taken for ten-minute periods at intervals of one-half to one-hour during the test run. Observations were made from the roof of the building, and in most cases, trees were used as the observation background.

An across stack transmissometer also was used during the test program to continuously monitor the stack gas opacity. The transmissometer consists of an incandescent light source on one side of the stack transmitting a light beam to a photovoltaic cell on the other side of the stack. The photocell is calibrated to measure any attenuation of the light by the stack effluent. A strip chart recorder is used to continuously record the transmissometer output. The transmissometer was designed and built according to the specifications of the smoke generator required for Reference Test Method 9. Briefly these specifications require the following:

1. A photopic spectral response of the photocell
2. A photocell angle of view less than or equal to 15 degrees
3. A light source angle of projection less than or equal to 15 degrees
4. A calibration error less than or equal to ±3 percent opacity (at three opacity levels)

5. A response time of less than 5 minutes

6. A zero/span drift of less than ±1 percent opacity in 30 minutes

A calibration was conducted prior to initiating the test program and then repeated again in the middle of the program and at the end of the program. Cleanliness of the photocell and light source were routinely checked and no problems were encountered in this regard.

Creosote

Creosote deposition was measured by suspending a small steel plate in the flue during the test burn; the plate was suspended from the top of the stack by a fine wire. The plate was tared before use and the subsequent weight gain due to creosote deposition during the test burn was gravimetrically determined. The plates measured 3 x 5 inches yielding a calculated surface area of 0.21 ft^2 (1.94×10^{-2} m^2) for two sides.

The creosote collection plates were placed at two different locations during the emission testing. One plate was lowered into the stack to a level just above the particulate sampling location. A second plate was lowered into the stack to a level near the transmissometer. Consequently, two different samples were simultaneously collected for each run.

Bacharach Smoke Spot Density

The Bacharach Smoke Spot tester was utilized to periodically measure smoke density during the emissions test. This device consists of a hand operated pump which is used to draw a sample from the stack and through a "spot" of filter paper. The degree of soiling of the filter is then visually determined by comparison to a numerically indexed chart. The smoke spot index is from 0 (no soiling) to 9 (maximum soiling). This device is frequently used to check soot levels in the effluent of boilers. The manufacturer suggests that 10 strokes of the hand pump be used for each sample (i.e., ten units of gas are drawn through the filter for each spot test). However, during the initial tests it was found that, due to the high emission levels, ten strokes of the pump resulted in an excessive sample. Consequently, during the remainder of the test program duplicate samples were taken; one sample with five strokes and one sample with ten strokes. Only the five stroke sample is reported, since this technique provided the better sample (soiling ranges of 4 - 9).

For the smoke spot test multiple sampling locations were used to determine if there might be a variation in results due to location within the flue. Samples were routinely taken from two locations; the sampling location for gaseous emissions, and the stack outlet. Results for both locations are reported.

Wood Moisture Determination

Wood moisture was determined for each piece of firewood fueled. The moisture content was measured and recorded within one day of its use. A Delmhorst Moisture Meter operating on the principle of electrical resistance was utilized for these measurements. This type instrument is typically used for measuring moisture content of lumber and timber.

In addition to these measurements several wood samples were analyzed for moisture content using ASTM procedure D 2016 "Moisture Content of Wood". In this procedure a cross section of the log is cut and weighed prior to and after heating to 211° F (105° C) to determine the percentage weight loss due to water evaporation. These tests were conducted strictly as a quality assurance check.

Net Efficiency Calculation

The net efficiency calculations presented in this report are based on the heat loss method. In this method the useable heat obtained from the appliance is calculated as the difference between the energy input and the heat loss in the effluent gas stream. The energy input is calculated from the gross calorific value and mass of fuel used during the test. The heat loss is calculated as the sum of the sensible and latent heats of the components of the effluent stream. During these tests, the volumetric flow of the effluent stream was calculated from a Stoichiometric Mass Carbon balance. The method used assumes all carbon is accounted for in the measured quantities of carbon monoxide, carbon dioxide, particulate (assume 70% carbon), and gaseous hydrocarbons (measured as Hexane). The calculated volumetric flow is used to calculate the sensible and latent heat losses. All other energy is considered usable. The basic equation is as follows:

$$\text{Net Efficiency, \%} = \frac{\text{Heat Input - Heat Loss}}{\text{Heat Input}} \times 100$$

The complete procedure used is presented in Appendix A.

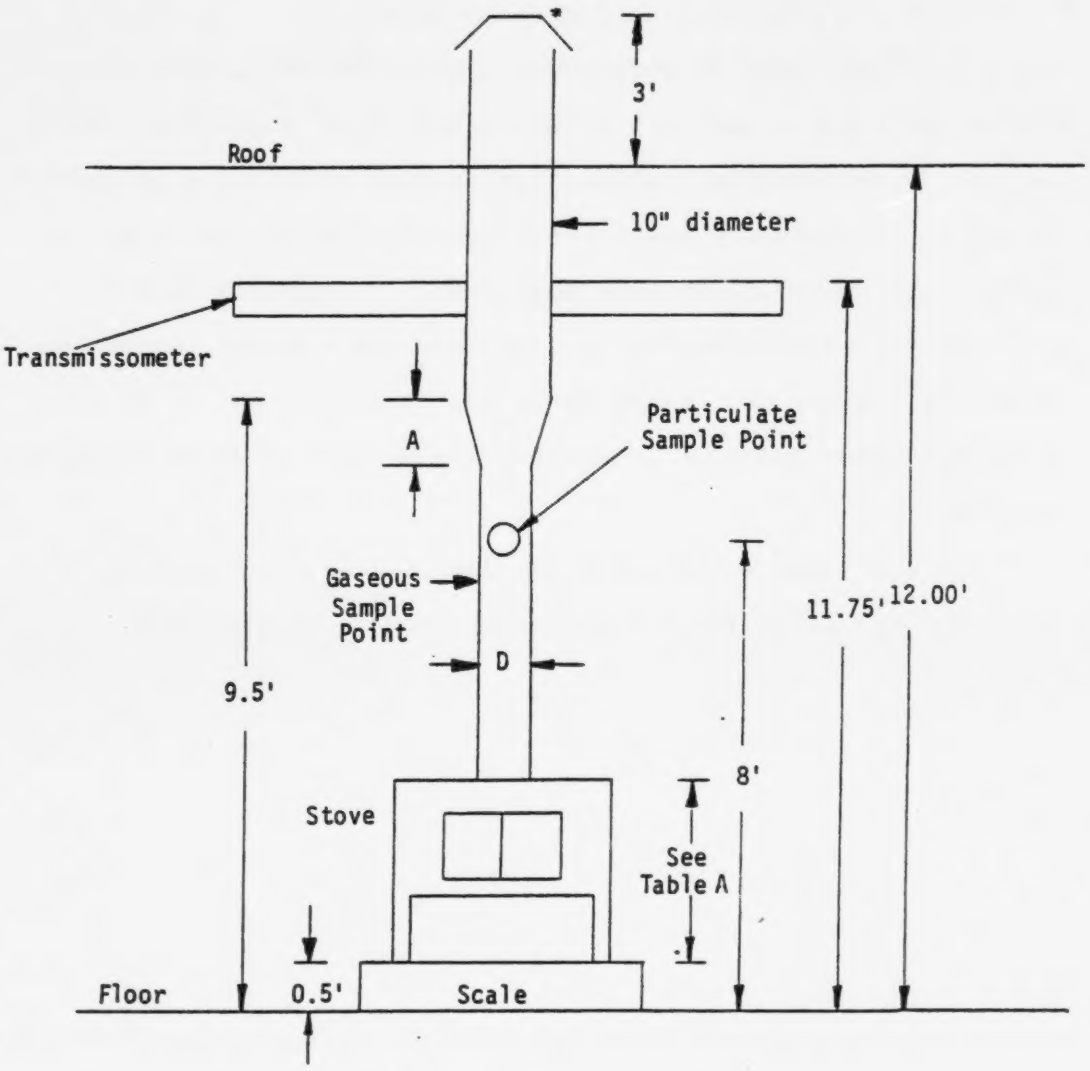
TEST SITE AND SAMPLE LOCATION

Figure 3 is a schematic diagram of the testing site. The stove being tested was placed on an electronic platform balance to continuously monitor the change in wood mass during the test burn. A slip joint section was used in the flue pipe to allow slight movement of the stove and platform, as well as to accommodate expansion and contraction of the flue pipe. All Method 5 particulate samples were taken through a single port located approximately 8 stack diameters from the stove exit. Gaseous samples were drawn from a sample port located approximately one foot lower in the duct. A transmissometer system was permanently located above the Method 5 sampling location.

This entire sample site set-up was located in an indoor unheated area. During testing, the rain cap was removed from the stack exit.

FIGURE 3

Test Site Configuration


*
3'
Roof
10" diameter
Transmissometer
A
Particulate
Sample Point
Gaseous
Sample
Point
D
9.5'
11.75'
12.00'
8'
Stove
See
Table A
Floor
0.5'
Scale

* Rain cap removed during testing

A - Length of reduction is 0.6' when D = 8" and is 1.3' when D = 6".

D - 8" for all runs except Runs 14 and 15 when D = 6".

FIGURE 3, TABLE A

Stove	Height (Inches)
Box Stove	30
Box Stove/Catalytic Add-on	42
Catalytic Box Stove	33
Ceramic Stove	12
Catalytic/Modified Combustion Stove	33

STOVE DESCRIPTIONS

AIRTIGHT BOX STOVE

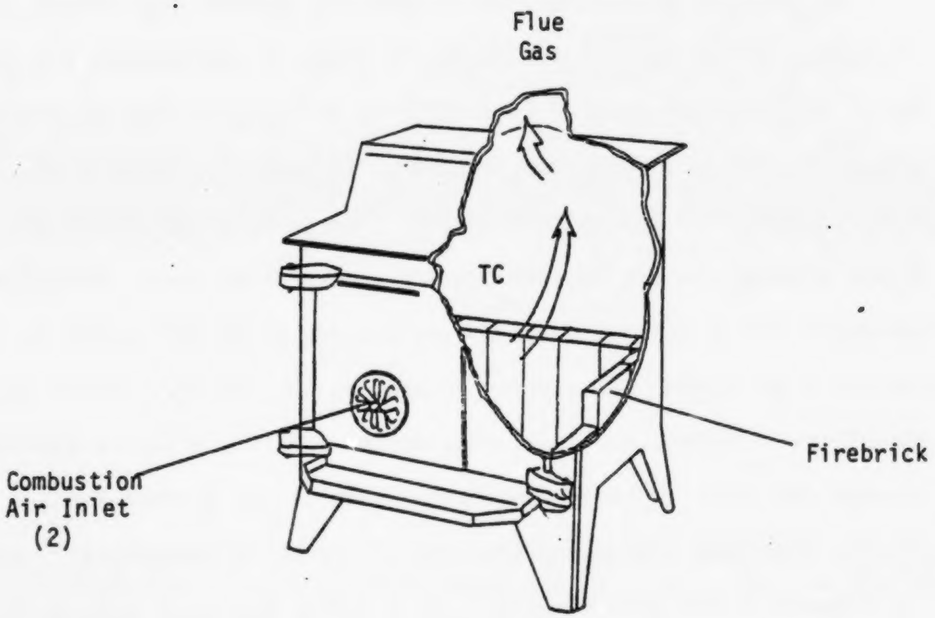
This stove is typical of the standard airtight stove constructed of plate metal and welded at the seams. Figure 4 is a schematic of the stove. The stove and hence the fire box are basically a simple large box. In this case the fire box was lined with firebricks. Two ports on the front of the stove are used to adjust combustion air. This stove did not include any internal baffles, or other combustion modifying devices, nor did it have any fans or blowers to aid in heat transfer.

The fire box on this stove has a volume of 4.9 cubic feet and an approximate surface area (six sides) of 22.5 square feet. The manufacturer suggests that this stove will heat a space of 1250-1750 square feet; no Btu output ratings are given.

During testing, the thermocouple for monitoring combustion chamber temperature was placed through the back of the stove at the center of the horizontal axis, and just above the top of the firebrick.

FIGURE 4

Airtight - Box Stove*


Flue
Gas
TC
Firebrick
Combustion
Air Inlet
(2)

TC - Thermocouple
* Not to scale

CATALYTIC STOVE

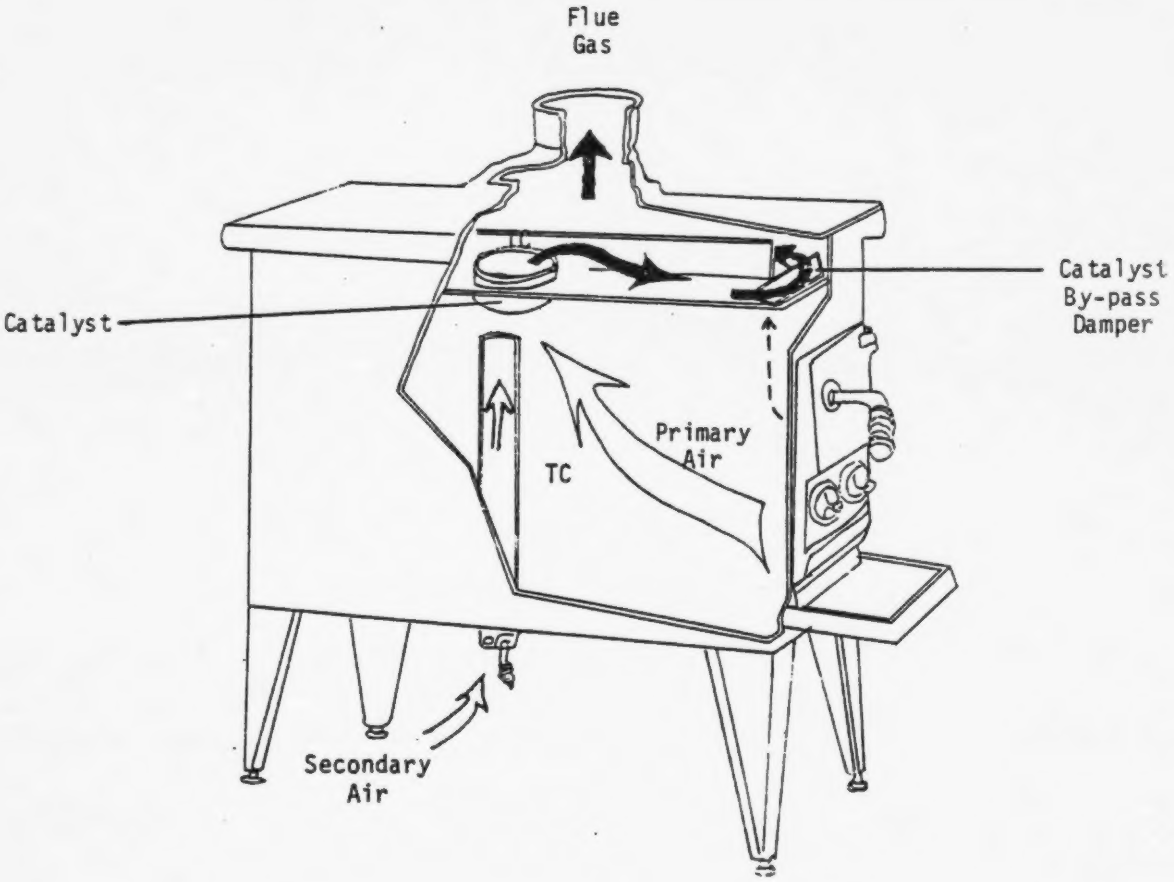
This stove's configuration is typical of an airtight box stove, although the stove has several modifications to accommodate the catalytic combustor. A schematic of the stove is presented in Figure 5. It is of welded plate steel construction. The firebox is lined with refractory brick on the bottom and partially up the side walls. The fire box on this stove is relatively long and narrow (28 X 11 inches) with a total volume of 2.6 cubic feet. The approximate surface area of this stove is 25.4 square feet. Charging of the stove is done through a single door on the narrow end of the stove.

As previously mentioned this stove has several significant modifications to the typical box design in order to accommodate the catalyst. The catalyst used in this stove is of the precious metal type coated on a ceramic honeycomb support. The honeycomb support in this model stove is six inches in diameter. The primary combustion air enters through two air control dampers on the stove door. Preheated secondary air is controlled by a separate mechanism and is fed in to the stove at a point immediately preceeding the catalyst. After passing through the catalyst the gases flow around a baffle prior to exiting through the flue. This extended pathlength of the exhaust fumes permits additional residence time within the stove theoretically enhancing combustion and heat transfer. As a safety device to prevent back flashing out the door, a catalyst by-pass damper is automatically activated whenever the charge door is open. This by-pass is located just inside and above the door, and consequently permits an immediate increase in draft and influx of air whenever the door is opened. This stove does not include any fans or additional heat exchangers to aid in heat transfer.

During the testing a thermocouple was placed into the firebox at a point midway down (horizontal axis) the back wall and about eight inches above the top of the firebrick lining. In addition, a second thermocouple was placed just above the catalytic combustor in order to monitor the temperature of the gases exiting the combustor.

FIGURE 5

Catalytic Stove*



Flue Gas
TC
Catalyst
Catalyst By-pass Damper
Primary Air
TC
Secondary Air

TC - Thermocouple

* Not to scale

CATALYTIC MODIFIED COMBUSTION STOVE

This stove encompasses several unique features (atypical of the basic box stove) only one of which is a catalytic combustor. Figure 6 is a schematic of the stove. The firebox of this stove is basically rectangular in shape with charging conducted through a single door on the stove's end. The combustion chamber on this stove is not firebrick lined. The combustion chamber volume is 3.0 cubic feet. Surface area of the stove is estimated at 35 square feet.

First of all, note that this stove does not use the ceramic honeycomb configuration for support of the catalyst medium. Although a precious metal catalyst is utilized, it is coated on one surface of flat ceramic "plates" of the stove manufacturer's own design. The plates are located at the top of the combustion chamber with two series of plates running the length of the chamber; one set of plates on each side of the chamber. During operation, the effluent gas stream is swept across the catalyst coated plate surface prior to exiting the stove.

In addition to the catalyst, the other design feature of this stove directed at increasing the combustion efficiency is the control and direction of the combustion air paths. Both primary and secondary combustion air enter through a single thermostatically controlled air inlet damper. The primary air is directed up through the grating supporting the burning wood, whereas the secondary air, after preheating, is directed into the firebox chamber just above the burning wood mass. The effluent gases pass upward to the top of the combustion chamber where the gases are directed by a set of baffles across the surface of the catalyst coated plates. After passing over the plates, the gases again are directed over a series of baffles to induce mixing and enhance combustion, prior to exiting through the flue pipe. In this design, tertiary combustion air also is used. The tertiary air enters the stove at the level of the wood grating via a manually operated air damper. The air first travels the length of the stove via a channel next to the wood grate, travels up a channel in the back of the stove and then is directed through holes in the catalyst plates to mix with the effluent combustion gases at the catalyst plate surface.

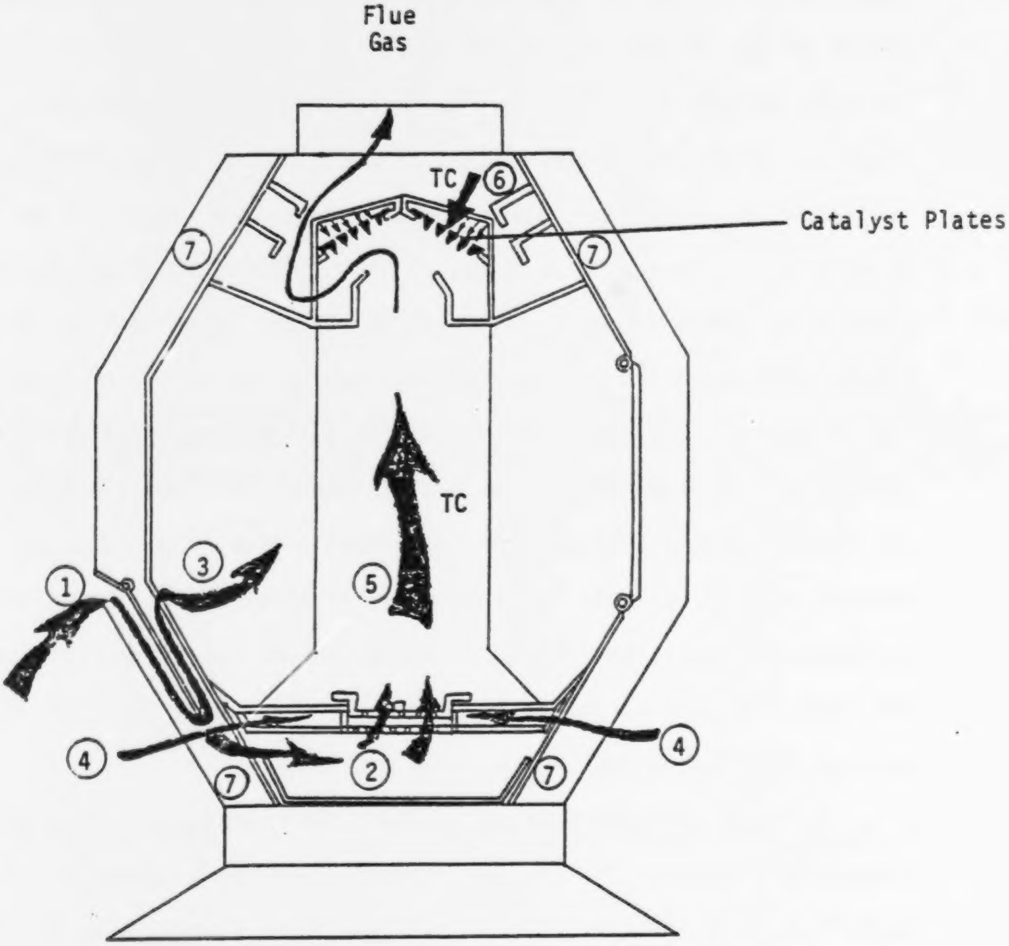
This stove does not utilize blowers to increase heat transfer. However, finned heat exchangers are located along the surface of the stove to increase heat transfer. These exchangers are located between the firebox and the stove's outer shell.

During the emission testing, thermocouples were placed at three locations within the stove chamber. These locations included the firebox chamber, the "third level air stage" just prior to the catalyst, and the post catalyst stage. These locations are depicted in Figure 6.

Prior to conducting the emissions testing, discussions with the manufacturer indicated minimum temperatures of 400°F for the tertiary air and 650°F for the combustion chamber were required in order to achieve catalytic reaction. Consequently, these temperatures were considered as necessary minimum values during the emission testing.

FIGURE 6

Catalytic - Modified Combustion Stove *


Flue
Gas
TC
⑥
Catalyst Plates
⑦
⑦
TC
③
⑤
①
④
②
④
⑦
⑦

1. Primary/Secondary air inlet
2. Primary combustion air
3. Secondary combustion air
4. Tertiary air inlet
5. Tertiary air (through channel up stove back)
6. Tertiary air inlet at catalyst
7. Heat exchange fins

* Not to scale

TC - Thermocouple

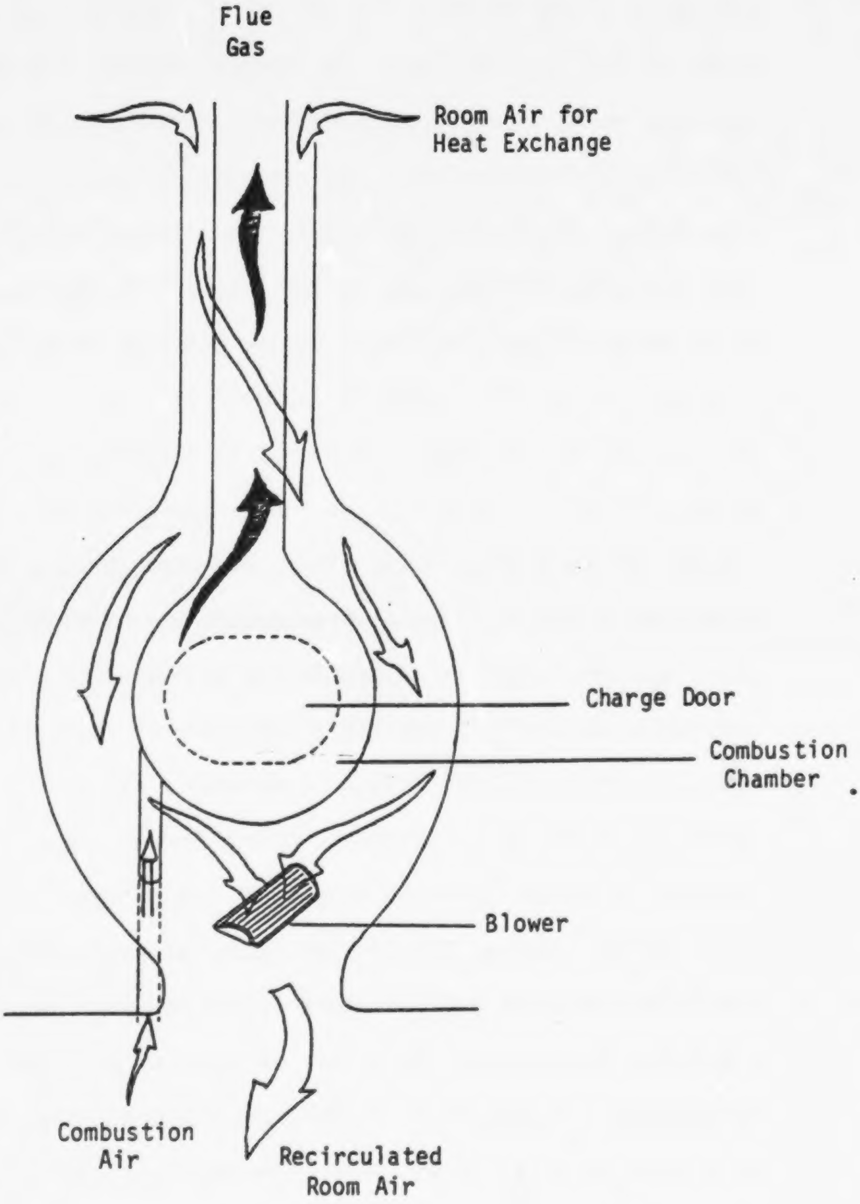
CERAMIC STOVE

The ceramic stove tested is significantly different in design than the typical steel plate welded box stove. Figure 7 is a schematic of the stove. The entire stove is cast in ceramic refractory material; the exterior then is covered in decorative tile. The firebox itself is spherical in shape with the combustion air entering near the bottom of the firebox and to one side. This air is preheated during its path through the refractory prior to entering the combustion chamber. On this particular stove there is no air inlet control; the only means of controlling the combustion rate is a damper in the flue, as well as the charge rate of wood. This is an interesting feature in regards to controlling air pollutant emissions, since this feature essentially means the operator cannot control the amount of combustion air; therefore, the stove is unlikely to be operated in an air starved condition. In order to promote heat transfer, this stove does have an air space (channel) between the combustion chamber and the outer ceramic shell. Room air is drawn downward through this channeling via a blower located at the bottom of the stove and then is distributed to the room from beneath the stove at floor level. Note that this blower was not operated during the emission testing.

A single airtight door is provided for charging the fuel to the combustion chamber. The chamber on this stove has a volume of 3.2 cubic feet (.08 m^3). Surface area of the stove is estimated at 22.3 square feet. No recommendations are provided by the manufacturer regarding estimated heat output or area space which this stove is capable of heating.

FIGURE 7

Ceramic Stove *


Flue
Gas
Room Air for
Heat Exchange
Charge Door
Combustion
Chamber
Blower
Combustion
Air
Recirculated
Room Air

* Not to scale

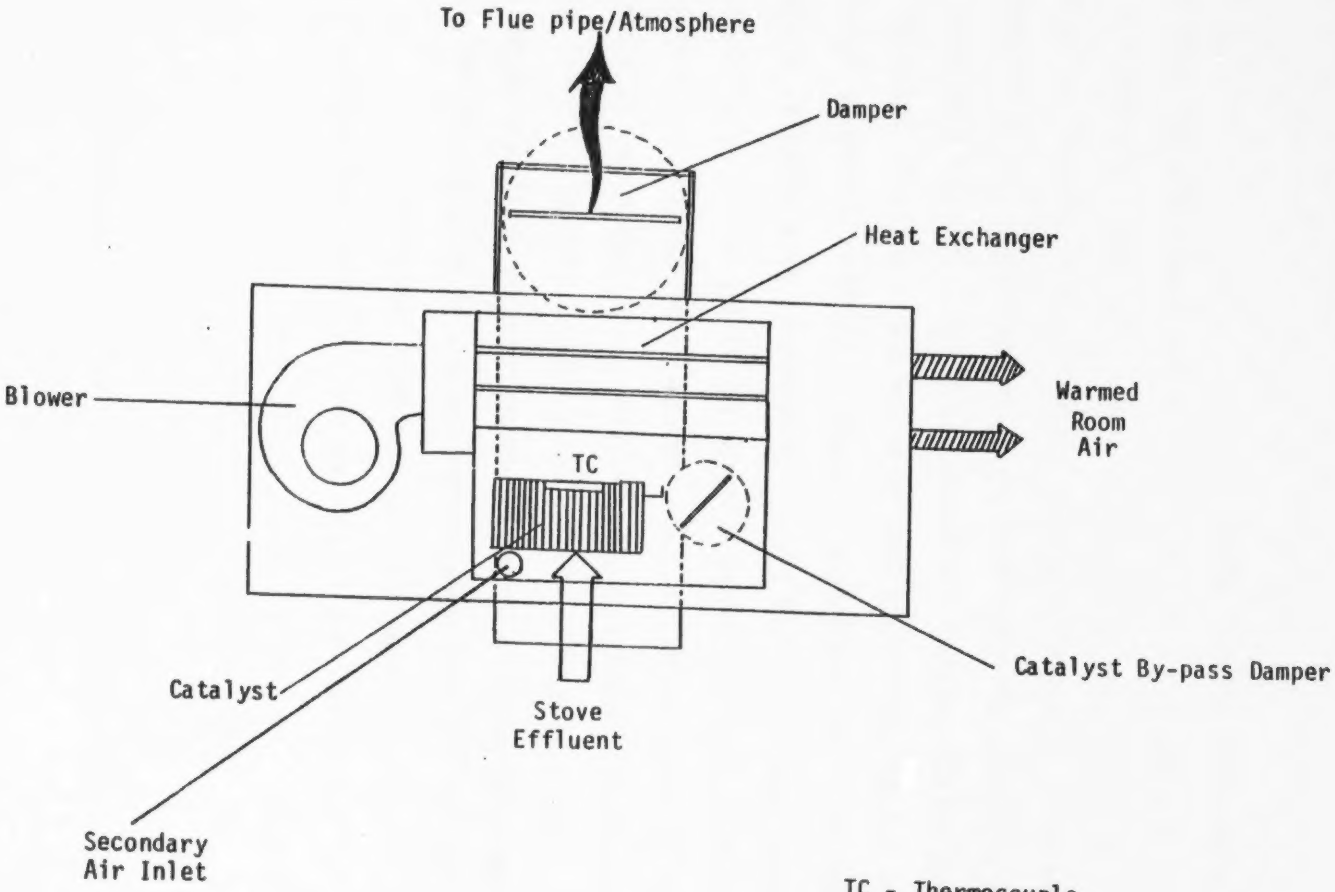
CATALYTIC RETROFIT DEVICE

This retrofit device is designed to add a catalytic combustor directly to the outlet of any typical wood stove. Figure 8 is a schematic of the device. The device is inserted into the flue at the point of the stove collar. The primary component of the system is the precious metal catalyst supported on a ceramic honeycomb. When the retrofit unit is installed, the catalyst sits directly above the stove flue outlet and the effluent gases are directed through the catalyst, over the heat exchanger and to the stack. The heat exchanger consists of an array of stainless steel tubing situated directly over the catalyst. A 140 CFM blower forces room air through the tubing to achieve the heat exchange. A damper is situated to provide a by-pass of the catalytic combustor. In normal operation this by-pass is closed, although even in the closed position about a 10% by-pass is permitted by design. The by-pass damper may be manually activated at any time; the damper is automatically activated by a thermostatically controlled solenoid if the operating temperature at the catalyst is below a certain minimum level. A secondary air control is provided to permit introduction of secondary combustion air just prior to the catalyst to assure adequate oxygen for combustion.

During testing, the by-pass damper was open during charging of the stove (catalyst off position). Once the stove was charged, the electronic control was set to the catalyst on position; the damper automatically closed once the catalyst reached a high enough temperature level to trip the solenoid. The unit was operated with the catalyst in operation throughout the remainder of the test burn. The blower serving the heat exchanger also was used during the test burns.

FIGURE 8

Catalytic Retrofit Device *


To Flue pipe/Atmosphere
Damper
Heat Exchanger
Blower
TC
Warmed Room Air
Catalyst
Stove Effluent
Catalyst By-pass Damper
Secondary Air Inlet

TC - Thermocouple
* Not to scale

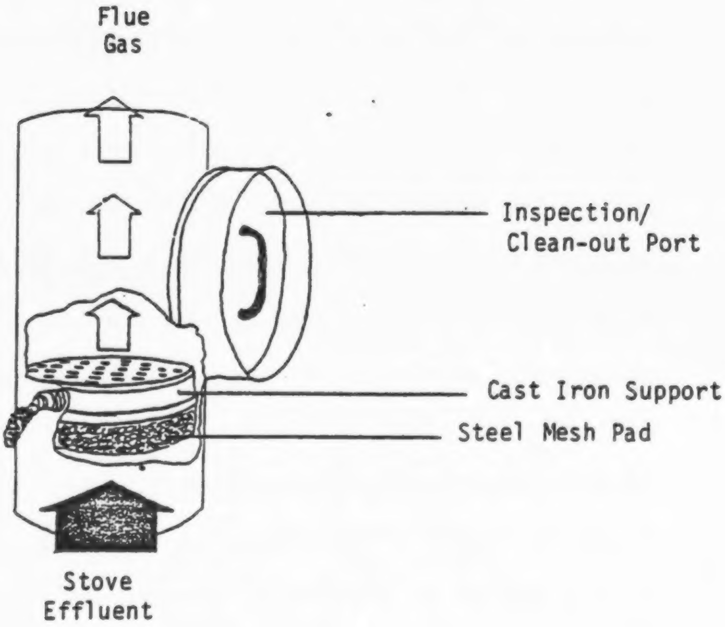
NON-CATALYTIC RETROFIT DEVICE

This device is inserted into the flue immediately following the stove outlet. The device consists of a large steel wire mesh pad mounted on a cast iron support. Figure 9 is a schematic of the device. In principle, the steel mesh traps any particulate in the effluent; once the particulate is trapped, one of two things may then occur. The trapped particulate remains on the pad, and thus is prevented from emission to the atmosphere; the particulate then is removed from the system when the pad is removed and cleaned. Alternatively, the particulate which accummulates on the pad during periods of stove operation at low temperatures, is combusted upon stove operation at elevated combustion temperatures when the steel pad's temperature is elevated to a point capable of combusting the entrapped particulate. Only ash will remain on the pad and this is removed from the system during pad cleaning. In this scenario, the pad acts first as a collector, then as a heat sink and reaction area to promote combustion.

This device does not include any additional heat exchangers or blowers.

FIGURE 9

Non-Catalytic Retrofit Device*


Flue
Gas
Inspection/
Clean-out Port
Cast Iron Support
Steel Mesh Pad
Stove
Effluent

* Not to scale

RESULTS

The results for each stove are presented separately in tabular and, in some cases, graphic format. A brief description of the tests is presented for each stove with special attention given to any problems encountered or anomalies in the data. Comparison of results among runs or between stove types, as well as interpretation of the results are presented in the Discussion of Results section of this report.

The first table in each subsection presents a complete listings of the emission results, as well as other important test parameters (e.g., burn rate). Where applicable, the results also are presented separately for each test run phase in a second similar table. Two separate tables present the results of the Bacharach smoke spot tests and the visible emissions opacity observations. Note that the Bacharach and the creosote measurements were both taken at multiple sample locations. Bacharach measurements were taken both at the gaseous emissions sampling port, as well as at the stack outlet (see Figure 3) and are reported as such. Creosote measurements were taken both at the sampling (Method 5) and transmissometer levels in the stack (see Figure 3). The creosote value reported in this section is the average value of the two measurements; the creosote results are presented separately for each sample location in the Discussion of Results Section (Table 44), as well as in the Appendix (Table B-2). Where applicable, a single table summarizing the temperatures measured before and after the catalyst is presented for each run.

Separate figures present the variation of the gaseous measurements (CO, CO_2, HC) as a function of time for each run and the variation of both stove surface and combustion chamber temperatures as a function of time. In both cases, the graphs were prepared using data recorded at five-minute intervals throughout the duration of the run. Similarly, a single figure presents the results of the emissions opacity data from both the visible emission observer and the transmissometer. The Bacharach smoke spot density results also are presented in the figure. The transmissometer data are plotted based on readings taken at ten-minute intervals. A single average value is plotted for each visible emission observation period which ranged from 5 to 30 minutes, depending on the test run. The smoke spot density for each measurement taken at the outlet location is plotted; generally, a measurement was taken approximately every 30-minutes.

Finally, the stove operations log for each test run is presented in tabular form. The operation log summarizes all changes made to stove operation (e.g., opening and closing of air inlet dampers) throughout the run and is presented in chronological order. The actual field data sheet on which stove operations were recorded is presented in Appendix E along with all other field data forms.

AIRTIGHT BOX STOVE

A total of nine test runs were conducted on the airtight box stove. Three tests (Runs 4, 6, and 8) were conducted with the stove starting from a totally cold condition. Since the purpose of these three tests were to determine if emissions during start-up of the stove would be significantly increased under cold start conditions, as compared to hot start conditions, the tests were short runs. Six other test runs were conducted, two test runs at each of three fuel moisture levels. Runs 1 and 7 were conducted with medium moisture fuel (20%, wet basis); runs 2 and 5 were conducted with dry fuel (12%, wet basis); and runs 3 and 9 were conducted with wet fuel (56%, wet basis).

Several minor anomalies occurred during the first few test runs. During Run 1, no creosote measurement was taken during phase 2 at the transmissometer location. In the second run, the first 20 minutes of transmissometer opacity readings were not valid since the creosote coupon was blocking the light transmission path. Due to the high fuel moisture content, problems in maintaining combustion were encountered during Run 8. Consequently, during this run, dry kindling had to be added during the test in order to maintain combustion. This run was from a cold start; similar operating problems were not encountered with the high moisture fuel during the hot start tests (Runs 3 and 9).

The average burn rate for the six normal test runs was 2.7 kg/hr with a range of 1.9 to 2.9. Average combustion chamber and surface temperatures were 580°F (513 - 650[a]) and 420°F (336 - 507), respectively.

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[a] Range

The average test time was 215 (189 to 275) minutes. Excess air ranged from 161 to 322 percent with an average of 206 percent for the six tests.

The average burn rate for the three cold start tests was 5.3 kg/hr (4.5 to 17.8). (This compares to an average burn rate of 4.0 kg/hr for the similar first phase of Runs 1 - 3.) Average combustion and stove surface temperatures were 580°F (470 - 675) and 400°F (233 - 575), respectively. The average test time was 80 minutes. Excess air for these tests averaged 225 percent.

TABLE 3

Results -- Airtight Box Stove

PARAMETERS	RUN NUMBER					
	1	2	3	5	7	9
Fuel Charge (lb, Wet)	26.2	27.4	34.5	26.0	28.3	27.6
(lb, Dry)	20.7	24.1	25.0	22.8	22.6	12.2
Fuel Moisture (%, Wet)	21	12	56	12	20	56
(%, Dry)	26	14	126	14	25	126
Sample Time (Minutes)	275	250	181	208	198	189
Fuel Burned (lb, Wet)	23.7	24.9	32.4	23.8	26.2	26.2
(lb, Dry)	18.7	21.9	14.3	20.9	21.0	11.5
Burn Rate (lb/hr, Wet)	5.2	5.9	10.7	6.9	7.9	8.3
(lb/hr, Dry)	4.1	5.3	4.7	6.0	6.4	3.7
Temperatures						
Combustion (°F)	513	543	654	569	610	600
Surface (°F)	336	435	361	450	507	427
Stack (°F)	265	316	342	299	372	361
Total Particulate Emissions*						
Concentration (g/dscm)	1.34	3.38	1.47	5.00	1.53	1.16
Rate (lb/hr)	0.09	0.28	0.16	0.37	0.12	0.08
Factor (g/kg wood, Dry)	22	54	34	62	19	22
(g/10^4 Btu, Net)	17	45	40	50	14	23
Front-half (% of total)	28.6	26.5	33.0	17.4	23.2	22.0
Creosote (mg/m^2 kg)	969	917	218	592	568	240
Hydrocarbons (ppm)	237	294	127	273	197	95
Hydrocarbons (g/kg wood, Dry)	13.8	16.9	10.5	12.1	8.8	6.6
Carbon monoxide (g/kg wood, Dry)	190	189	160	220	160	110
Opacity (observer, %)	36	34	20	37	28	11
Stack Gas Composition						
CO_2 (%)	4.8	4.4	3.6	6.1	7.0	4.7
CO (%)	1.0	1.0	0.6	1.5	1.1	0.5
O_2 (%)	15.3	13.7	14.2	14.0	13.5	16.1
N_2 (%)	80.7	80.9	81.6	78.4	78.4	78.7
Moisture (%)	-	-	-	8.3	6.2	7.2
Excess Air (%)	228	161	181	177	167	322
Stack Gas Flow (dscf/hr)	1060	1350	1750	1200	1270	1130
Efficiency, (net, %)**	65	60	43	62	66	48

---

*Oregon DEQ Method 7 (EPA Method 5 with back half)

** Since techniques for determining appliance efficiency vary tremendously, the reported efficiency results should be used only as relative values for comparison between stoves and test runs under the specific operating conditions of this program.

TABLE 4

Results -- Airtight Box Stove
(Cold Start Tests)

PARAMETERS	RUN NUMBER		
	4	6	8
Fuel Charge (lb, Wet)	29.7	27.3	38.1
(lb, Dry)	26.1	22.0	16.9
Fuel Moisture (%, Wet)	12	19	56
(%, Dry)	14	24	126
Sample Time (Minutes)	35	46	155
Fuel Burned (lb, Wet)	11.8	12.1	26.5
(lb, Dry)	10.4	9.8	11.7
Burn Rate (lb/hr, Wet)	20.2	15.8	10.3
(lb/hr, Dry)	17.8	12.8	4.5
Temperatures			
Combustion (°F)	675	598	470
Surface (°F)	575	388	233
Stack (°F)	544	401	295
Total Particulate Emissions*			
Concentration (g/dscm)	3.57	3.75	0.89
Rate (lb/hr)	0.72	0.54	0.11
Factor (g/kg wood, Dry)	40	42	24
($g/10^4$ Btu, Net)	36	34	27
Front-half (% of total)	23.9	19.7	25.4
Creosote (mg/m^2 kg)	216	291	109
Hydrocarbons (ppm)	294	227	115
Hydrocarbons (g/kg wood, Dry)	11.9	9.2	11.1
Carbon monoxide (g/kg wood, Dry)	210	170	190
Opacity (observer, %)	40	46	20
Stack Gas Composition			
CO_2 (%)	7.0	7.3	3.1
CO (%)	1.6	1.3	0.6
O_2 (%)	12.8	12.7	17.1
N_2 (%)	78.6	78.7	79.3
Moisture (%)	16.2	13.8	7.5
Excess Air (%)	137	138	407
Stack Gas Flow (dscf/hr)	3230	2320	1950
Efficiency, (net, %)**	56	62	44

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* Oregon DEQ Method 7 (EPA Method 5 with back-half)

** Since techniques for determining appliance efficiency vary tremendously, the reported efficiency results should be used only as relative values for comparison between stoves and test runs under the specific operating conditions of this program.

TABLE 5

Results -- Airtight Box Stove
(By Test Phase)

PARAMETERS	RUN NUMBER/PHASE					
	1/1	1/2	2/1	2/2	3/1	3/2
Fuel Charge (lb, Wet)	26.2		27.4		34.5	
(lb, Dry)	20.7		24.1		25.0	
Fuel Moisture (%, Wet)	21		12		27	
(%, Dry)	26		14		38	
Sample Time (Minutes)	68	207	42	208	80	101
Fuel Burned (lb, Wet)	11.8	11.9	9.4	15.5	18.5	13.9
(lb, Dry)	9.3	9.4	8.3	13.6	8.2	6.1
Burn Rate (lb/hr, Wet)	10.4	3.4	13.4	4.5	13.9	8.3
(lb/hr, Dry)	8.2	2.7	11.9	3.9	6.2	3.6
Temperatures						
Combustion (°F)	538	496	552	464	601	693
Surface (°F)	380	317	472	367	356	364
Stack (°F)	359	229	437	269	354	322
Total Particulate Emissions*						
Concentration (g/dscm)	0.79	1.74	7.01	2.28	1.55	1.37
Rate (lb/hr)	0.11	0.09	0.82	0.18	0.21	0.12
Factor (g/kg wood, Dry)	11	33	69	45	35	33
($g/10^4$ Btu, Net)	--	--	--	--	--	--
Front-half (% of total)	46.9	27.4	23.9	28.6	40.6	19.7
Creosote (mg/m^2 kg)	683	1051	725	1038	124	344
Hydrocarbons (ppm)	264	226	365	280	123	130
Hydrocarbons (g/kg wood, Dry)	12.9	15.2	12.9	19.8	9.8	11.1
Carbon monoxide (g/kg wood, Dry)	190	220	149	210	210	140
Opacity (observer, %)	36	37	47	33	22	19
Stack Gas Composition						
CO_2 (%)	6.2	4.2	8.1	3.9	3.6	3.6
CO (%)	1.2	1.0	1.3	0.9	0.8	0.5
O_2 (%)	11.9	16.2	12.6	13.9	13.2	15.0
N_2 (%)	80.8	78.6	78.0	81.3	82.4	80.9
Moisture (%)	7.2	4.9	17.8	5.7	10.9	7.0
Excess Air (%)	113	311	137	165	143	221
Stack Gas Flow (dscf/hr)	2310	820	1880	1250	2200	1390
Efficiency, (net, %)						

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* Oregon DEQ Method 7 (EPA Method 5 with back-half)

TABLE 6
Bacharach Smoke Spot Results

RUN	SAMPLE TIME	SPOT DENSITY	
		Sample Location	
		Sampling	Outlet
1	1413 - 1417*	9	9
1356-1831	1445 - 1447	8	7
	1530 - 1537	8	8
	1615 - 1620	7	6
	1645 - 1655	8	9
	1730 - 1735	2	2
	1820 - 1825	8	6
	1837 - 1840	-	4
	Ave. Temperature	253° F	163° F
2	1337 - 1341	9	9
1301-1711	1410 - 1412	9	8
	1441 - 1442	8	8
	1512 - 1514	8	7
	1545 - 1547	8	7
	1614 - 1615	4	2
	1704	2	-
	Ave. Temperature	281° F	158° F
3	1320 - 1324	6	6
1234-1535	1345 - 1347	8	7
	1410 - 1416	8	7
	1443 - 1444	6	6
	1510 - 1515	7	6
	Ave. Temperature	337° F	223° F
4	1018 - 1021	8	8
0959-1034	Ave. Temperature	292° F	180° F

TABLE 6 (Cont.)

RUN	SAMPLE TIME	SPOT DENSITY	
		Sample Location	
		Sampling	Outlet
5	1320 - 1339	8	7
1242-1610	1426 - 1428	8	7
	1453 - 1455	7	6
	1531 - 1533	5	4
	Ave. Temperature	249° F	163° F
6	0943 - 0945	8	8
0914-1000	Ave. Temperature	293° F	195° F
7	1254 - 1255	8	8
1149-1507	1315 - 1317	7	7
	1403	7	-
	1440	-	4
	Ave. Temperature	393° F	222° F
8	0935 - 0940	9	8
0905-1140	1012 - 1014	5	4
	1134 - 1137	4	4
	Ave. Temperature	331° F	247° F
9	1306 - 1308	7	6
1318-1627	1456 - 1458	7	7
	1540 - 1546	7	6
	Ave. Temperature	302° F	240° F

TABLE 7

Visible Emissions Observation Log

RUN	RUN TIME		VISIBLE EMISSIONS MEASUREMENT				
	Clock • Phase 1 • Phase 2	Elasped Min. • Phase 1 • Phase 2	Time Period	Minutes Observed	Opacity (Percent)	Opacity Range (Percent)	Average Opacity (Percent) Phases 1,2,total
1	1356 - 1504	68	1355 - 1424	30	38	15 - 60	36
	1504 - 1831	207	1424 - 1454	30	34	30 - 45	37
		275	1515 - 1544	30	38	30 - 45	37
			1545 - 1609	30	43	40 - 45	
			1620 - 1649	30	43	40 - 45	
			1650 - 1719	30	25	15 - 45	
2	1301 - 1343	42	1300 - 1341	41	47	5 - 60	47
	1343 - 1711	208	1341 - 1406	19	43	35 - 45	33
		250	1410 - 1439	30	42	35 - 45	34
			1440 - 1509	30	59	45 - 60	
			1515 - 1544	30	47	35 - 60	
			1545 - 1614	30	27	5 - 40	
			1615 - 1644	30	7	0 - 15	
			1645 - 1714	30	0	0 - 5	
3	1234 - 1354	80	1230 - 1259	30	28	10 - 60	23
	1354 - 1535	101	1300 - 1329	30	15	15	19
		181	1335 - 1404	30	25	20 - 40	21
			1405 - 1434	30	20	15 - 45	
			1435 - 1504	30	17	15 - 20	
			1505 - 1534	30	20	15 - 25	
4	0959 - 1034	35	1013 - 1017	5	40	30 - 50	40

TABLE 7 (Cont.)

RUN	RUN TIME		VISIBLE EMISSIONS MEASUREMENT				
	Clock · Phase 1 · Phase 2	Elasped Min. · Phase 1 · Phase 2	Time Period	Minutes Observed	Opacity (Percent)	Opacity Range (Percent)	Average Opacity (Percent) Phases 1,2,total
5	1242 - 1610	208	1315 - 1319	5	42	35 - 50	37
			1450 - 1554	5	41	30 - 55	
			1535 - 1539	5	28	20 - 30	
6	0914 - 1000	46	0940 - 0944	5	46	40 - 50	46
7	1149 - 1507	198	1233 - 1237	5	28	20 - 40	28
			1335 - 1339	5	36	25 - 40	
			1430 - 1434	5	19	15 - 20	
8	0905 - 1140	155	0940 - 0944	5	25	20 - 30	20
			1100 - 1104	5	14	10 - 20	
9	1318 - 1627	189	1347 - 1351	5	11	10 - 15	11
			1445 - 1459	5	14	10 - 20	
			1541 - 1553	5	7	5 - 10	

FIGURE 10

Run 1

Gaseous Component

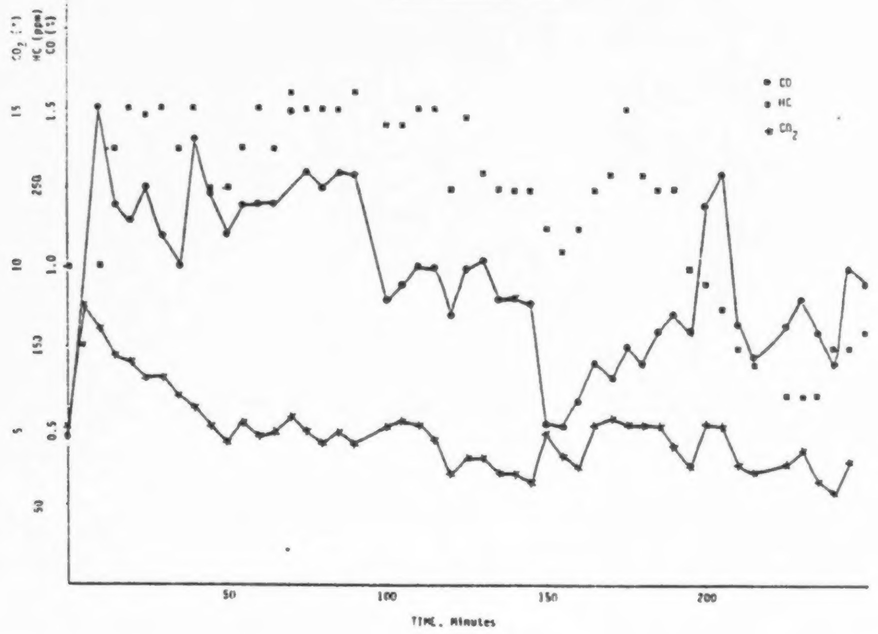


FIGURE 11

Run 1

Temperature

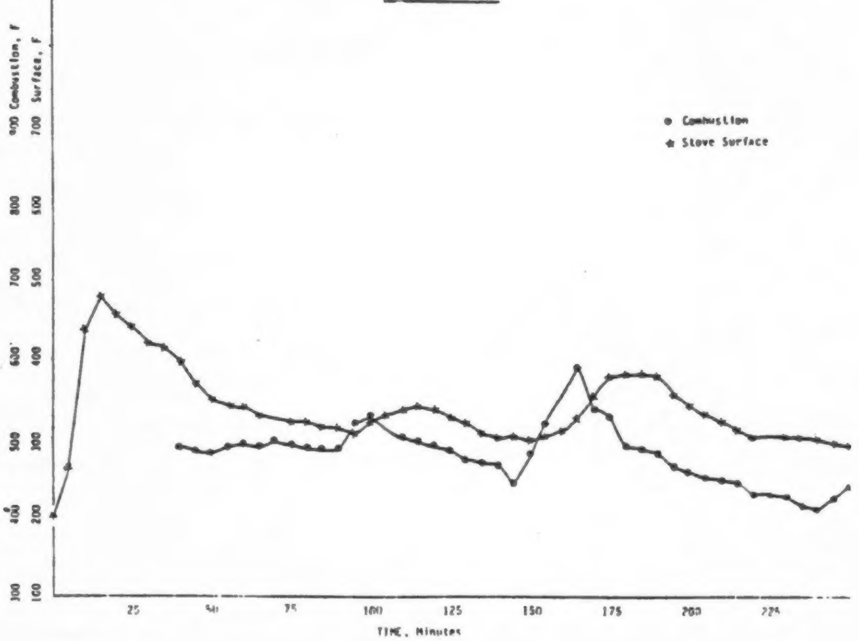
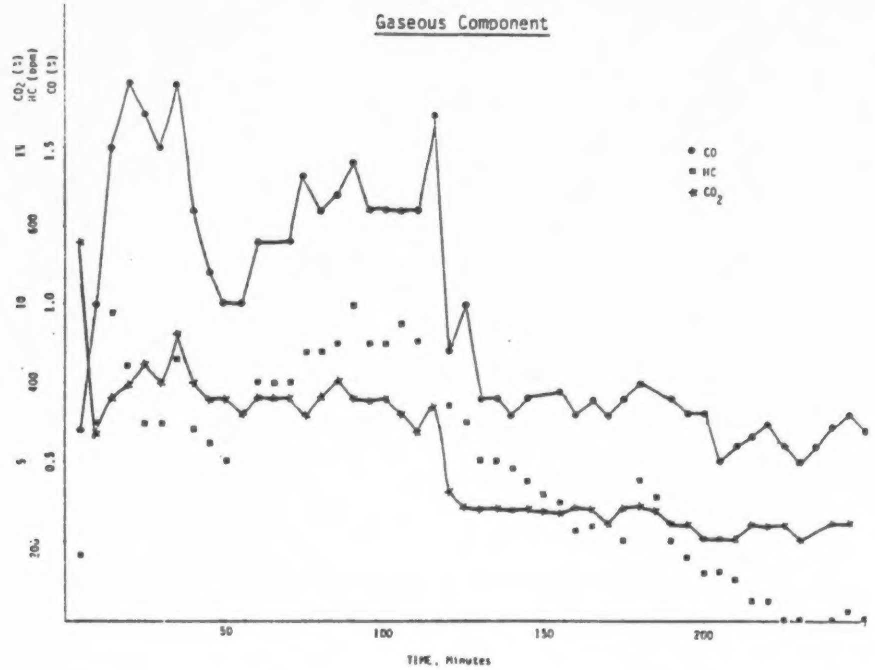


FIGURE 12

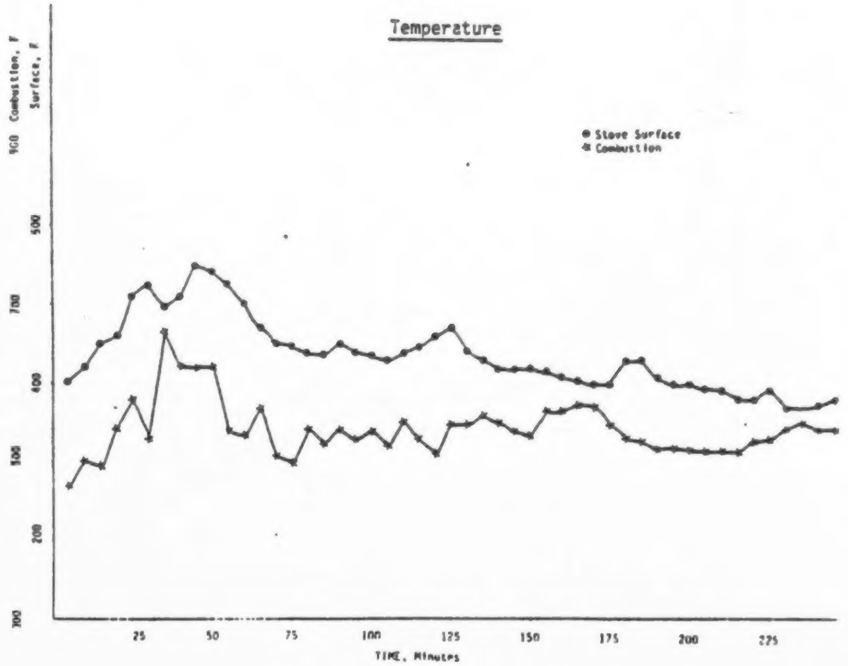
Run 2



Gaseous Component

FIGURE 13

Run 2



Temperature

FIGURE 14

Run 3

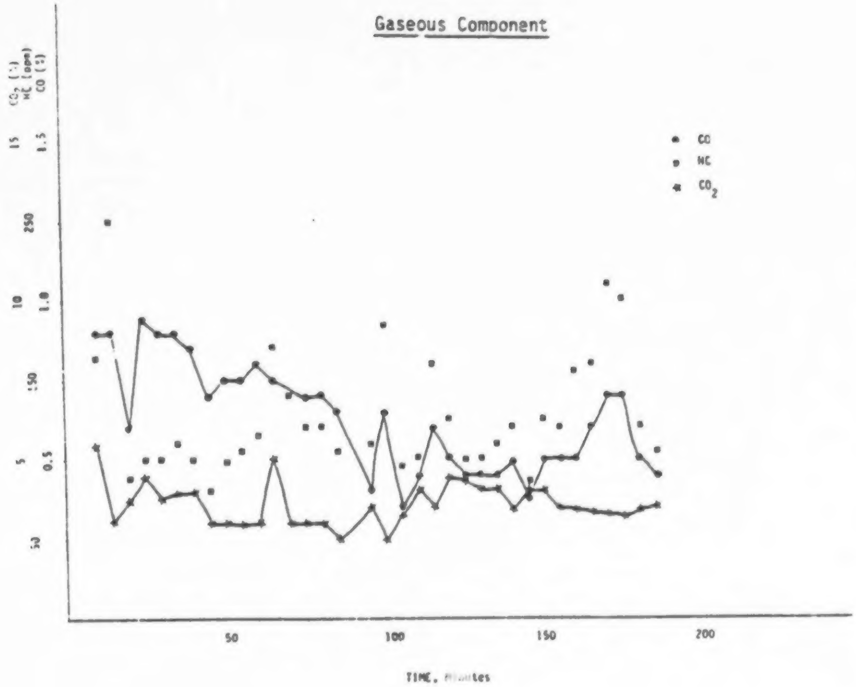

Gaseous Component

FIGURE 15

Run 3

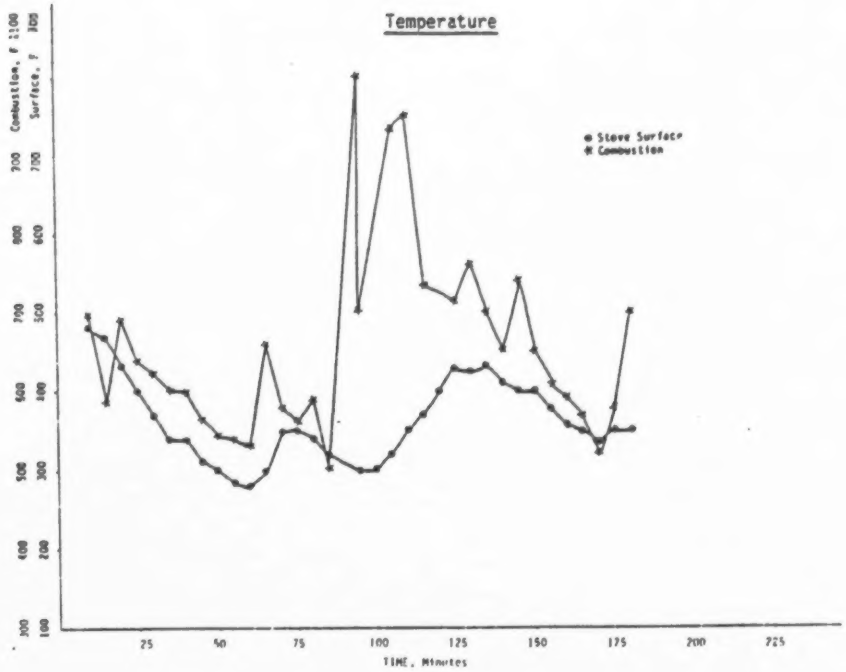

Temperature

FIGURE 16

Run 4

Gaseous Component

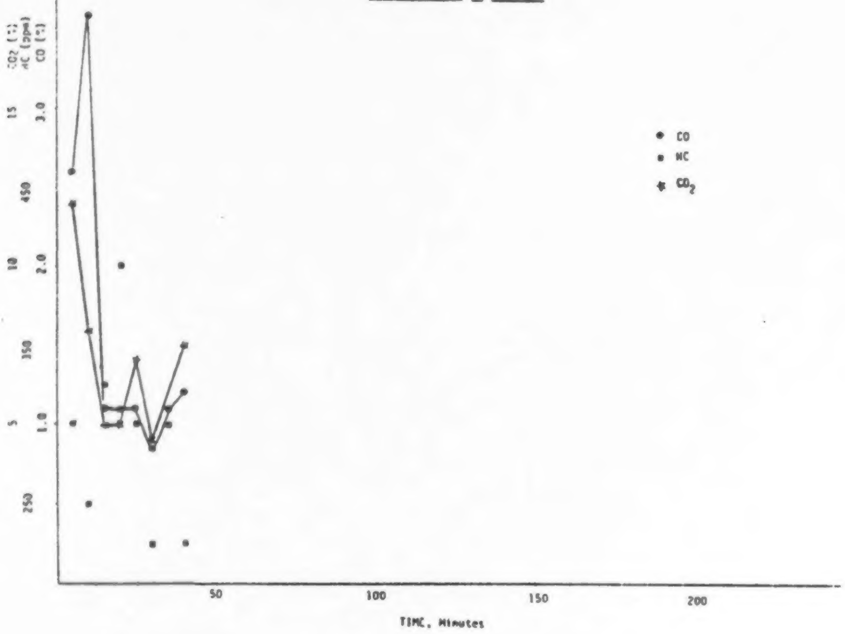


FIGURE 17

Run 4

Temperature

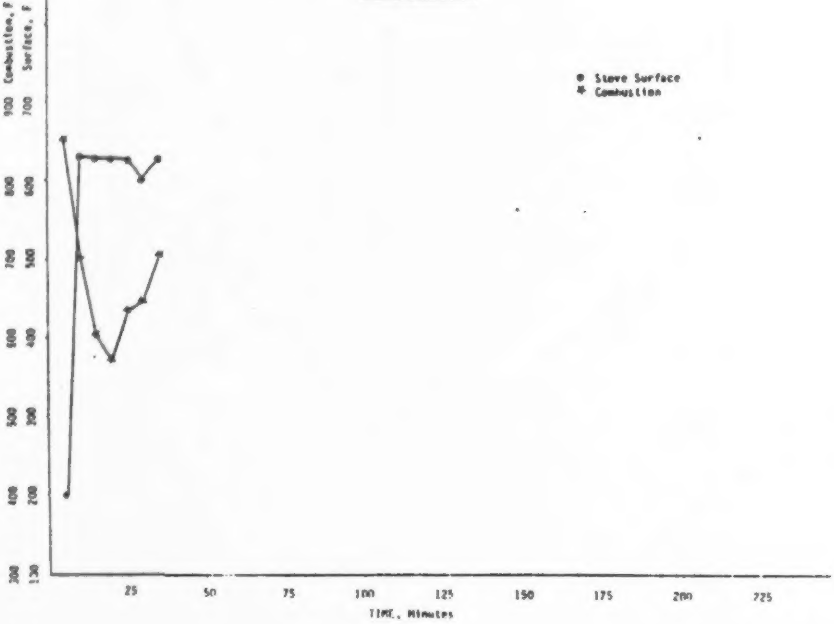


FIGURE 18

Run 5

Gaseous Component

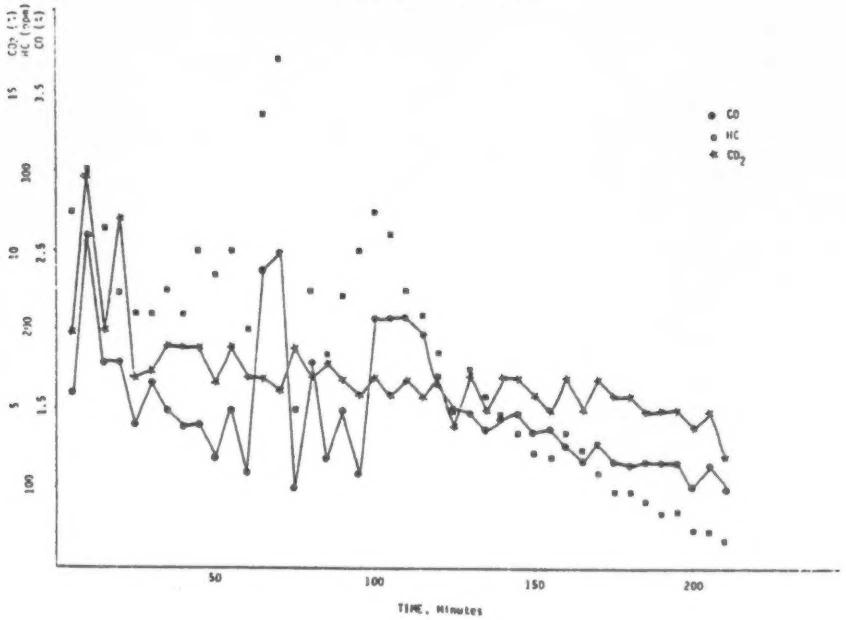


FIGURE 19

Run 5

Temperature

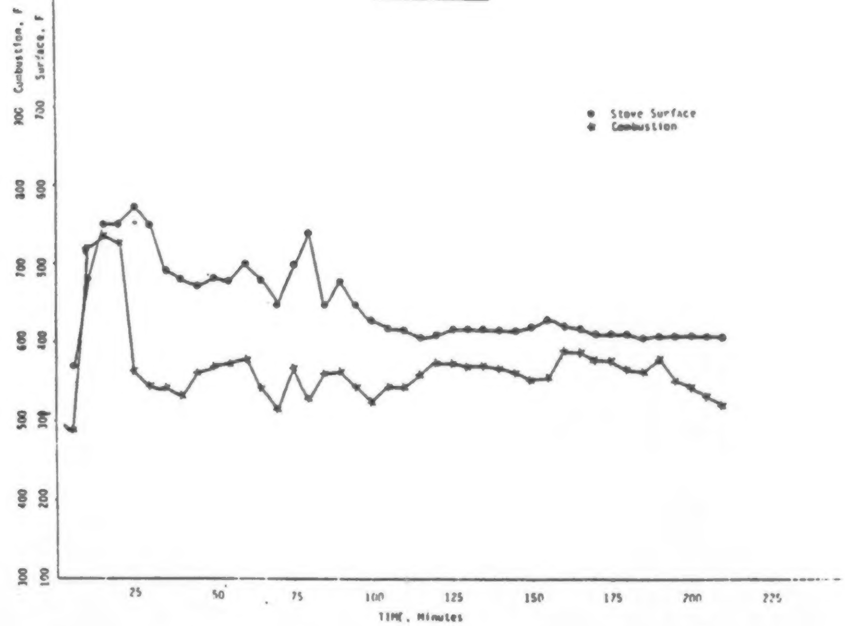


FIGURE 20

Run 6

Gaseous Component

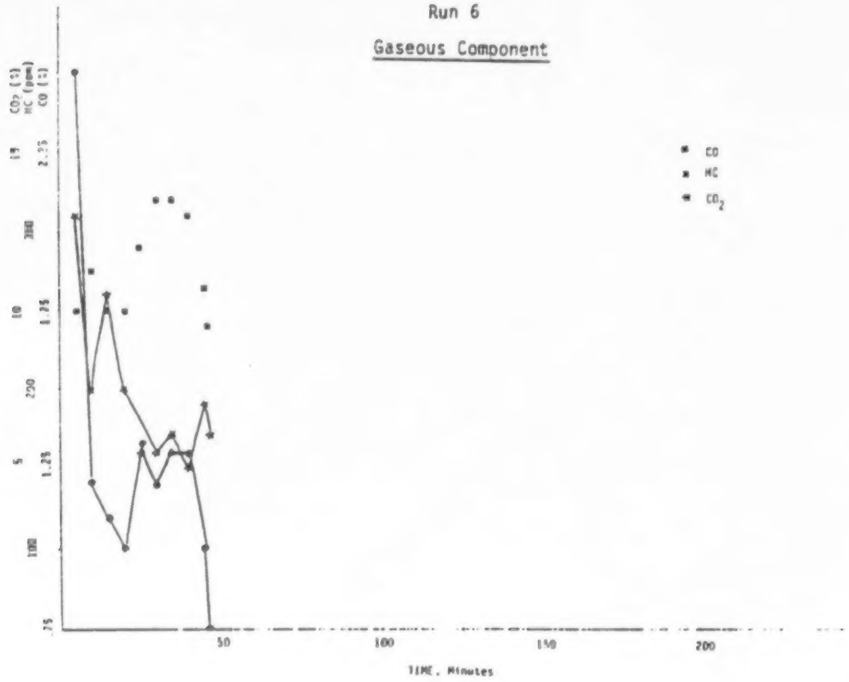


FIGURE 21

Run 6

Temperature

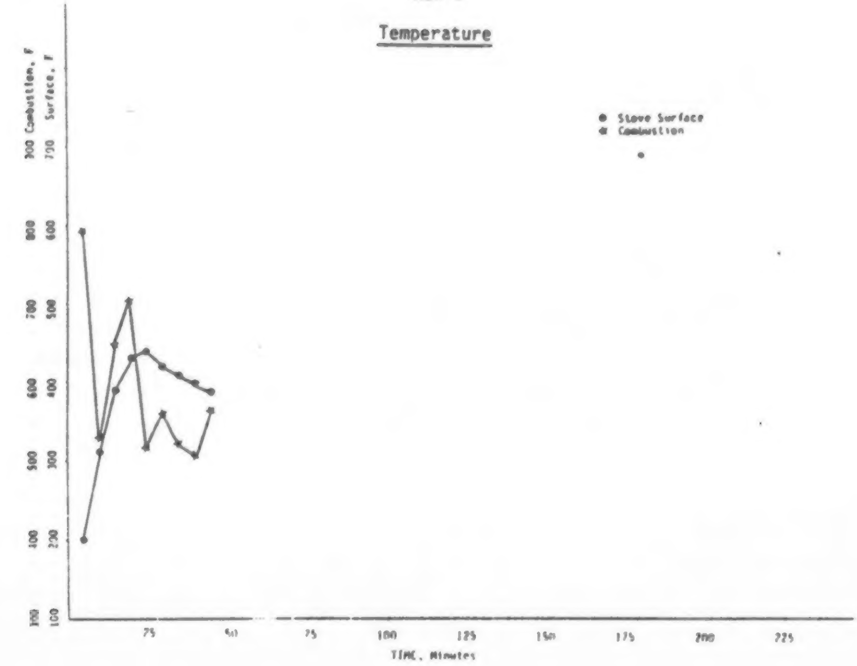


FIGURE 22

Run 7

Gaseous Component

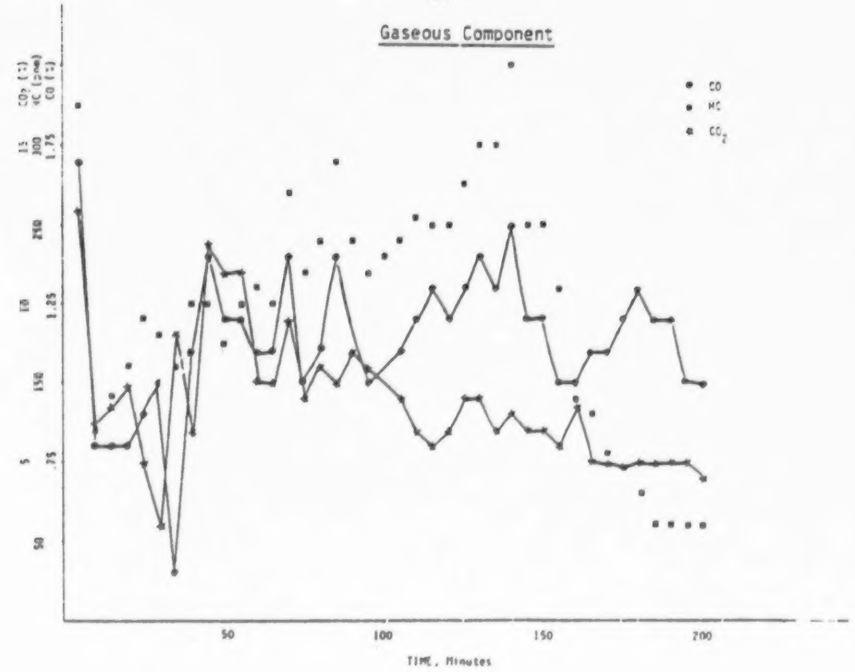


FIGURE 23

Run 7

Temperature

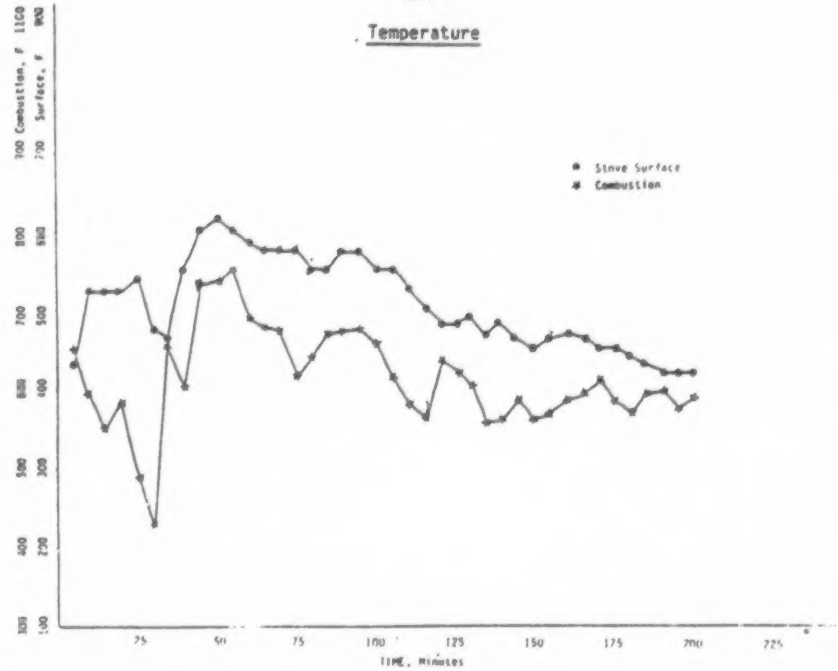


FIGURE 24

Run 8

Gaseous Component

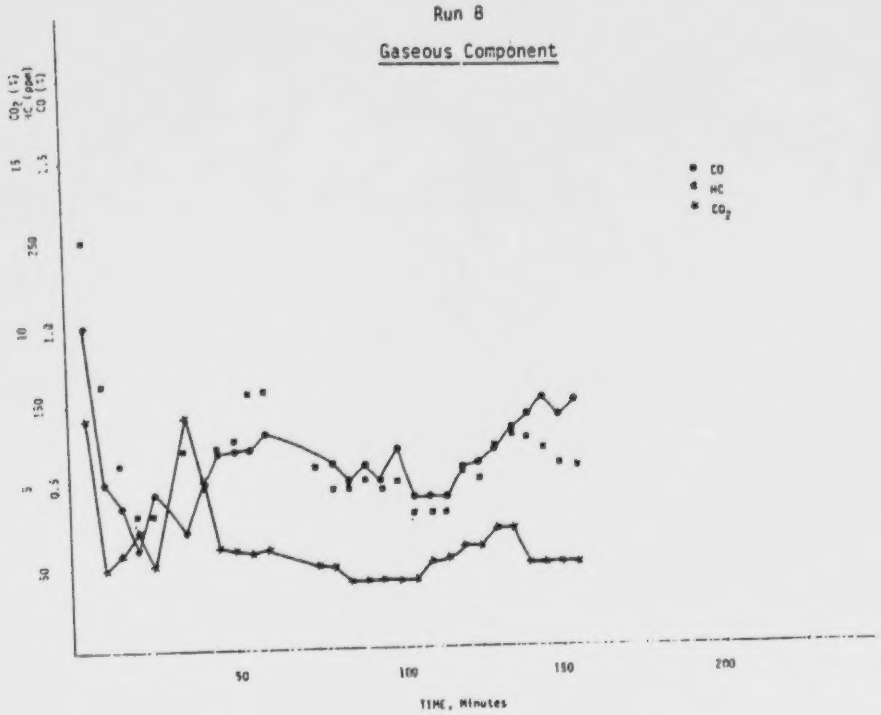


FIGURE 25

Run 8

Temperature

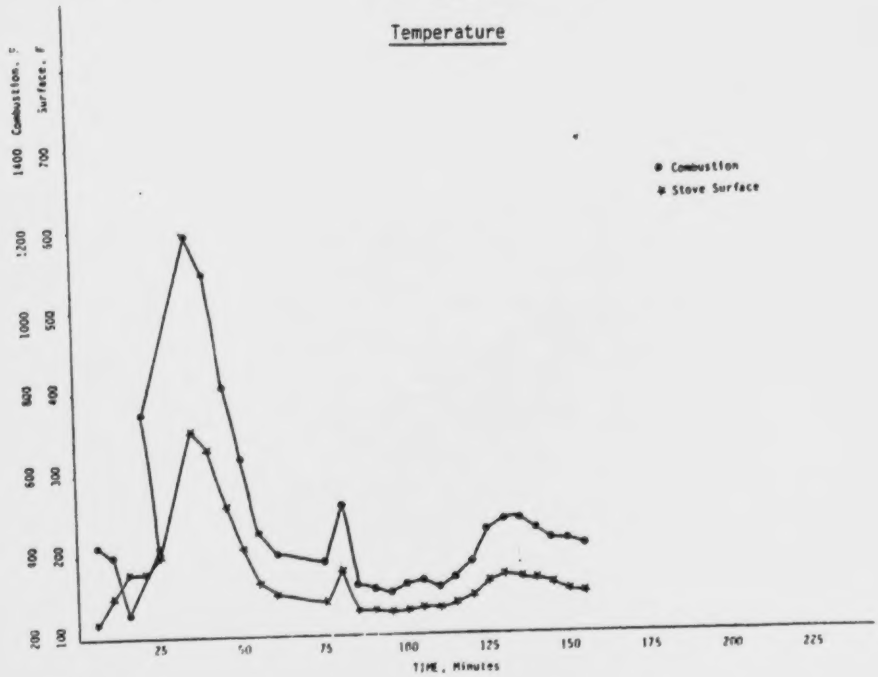


FIGURE 26

Run 9

Gaseous Component

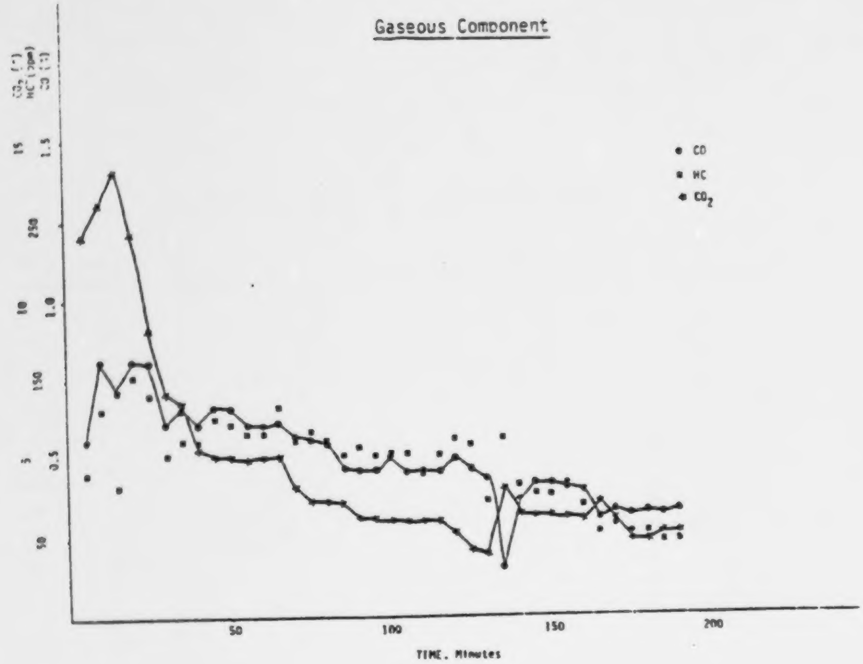


FIGURE 27

Run 9

Temperature

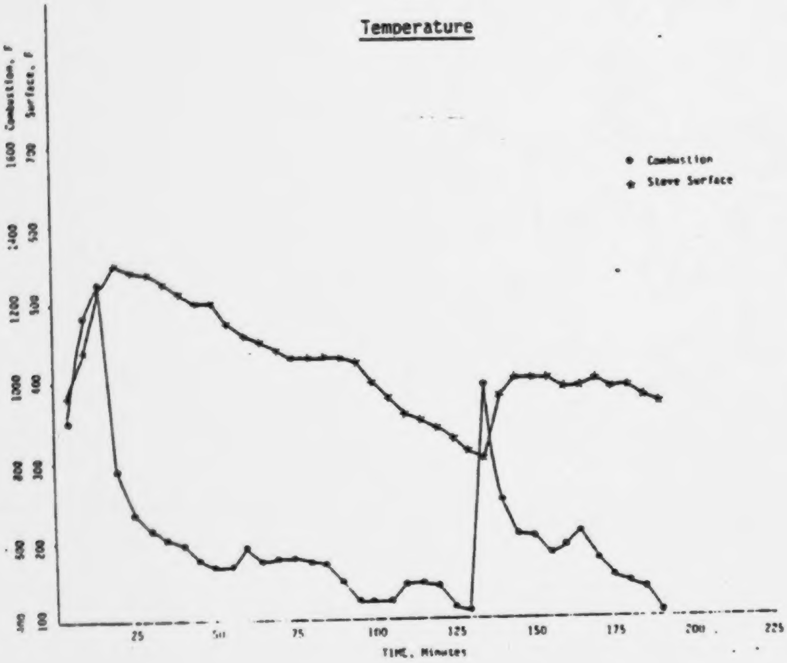


FIGURE 28

Opacity and Smoke Spot Density
vs
Time
(Run 1)

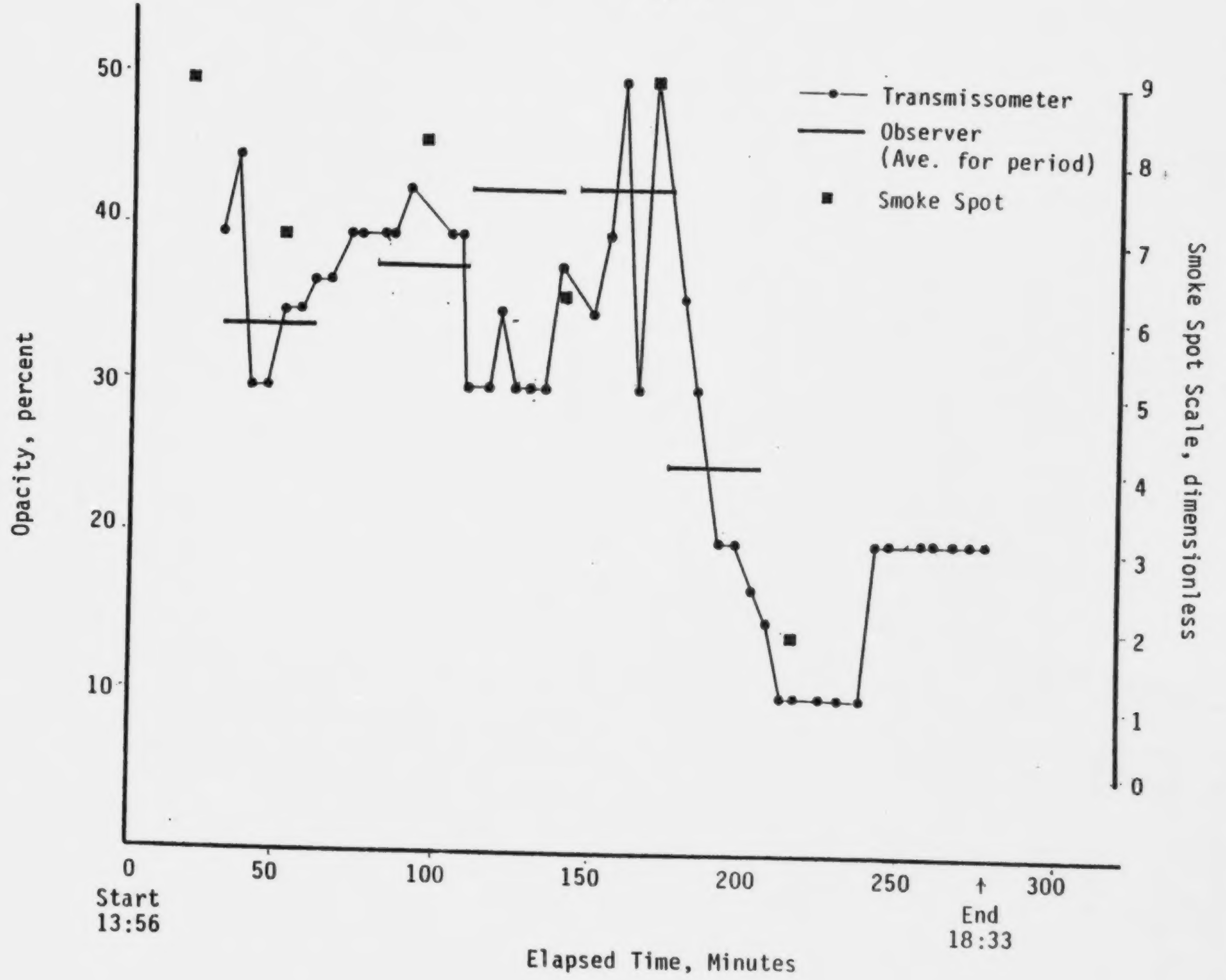


FIGURE 29

Opacity and Smoke Spot Density
vs
Time
(Run 2)

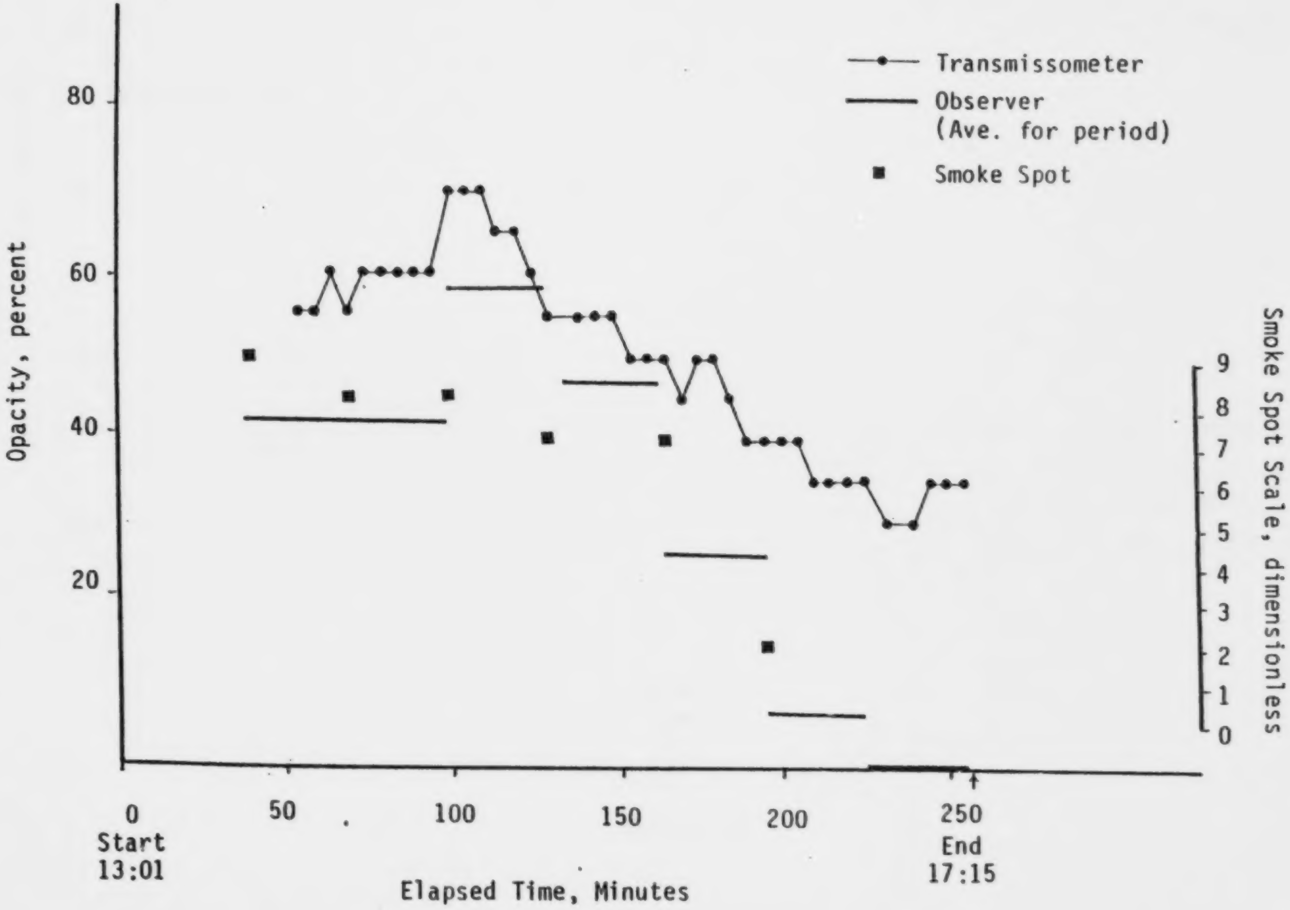


FIGURE 30

Opacity and Smoke Spot Density
vs
Time
(Run 3)

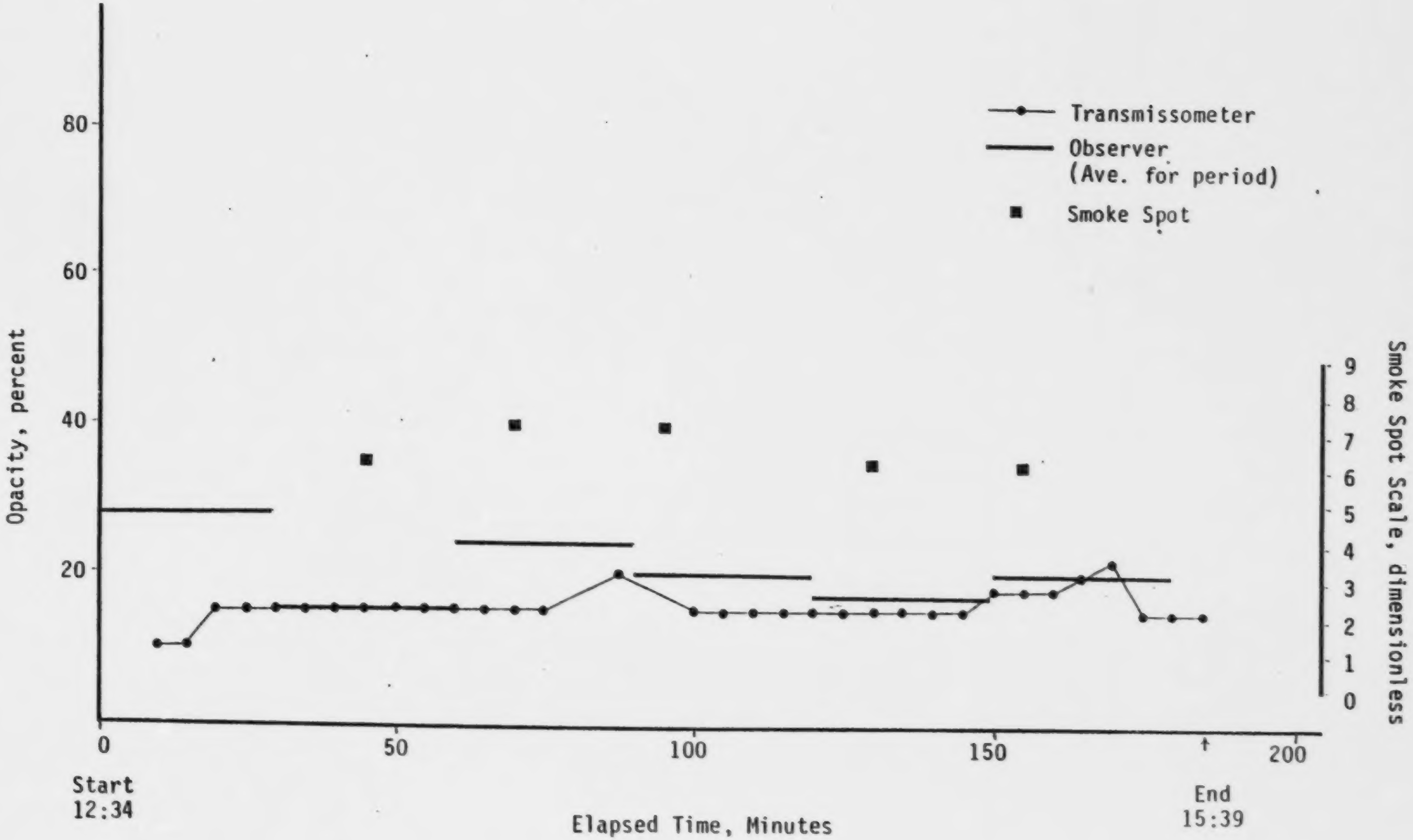


FIGURE 31

Opacity and Smoke Spot Density
vs
Time
(Run 4)

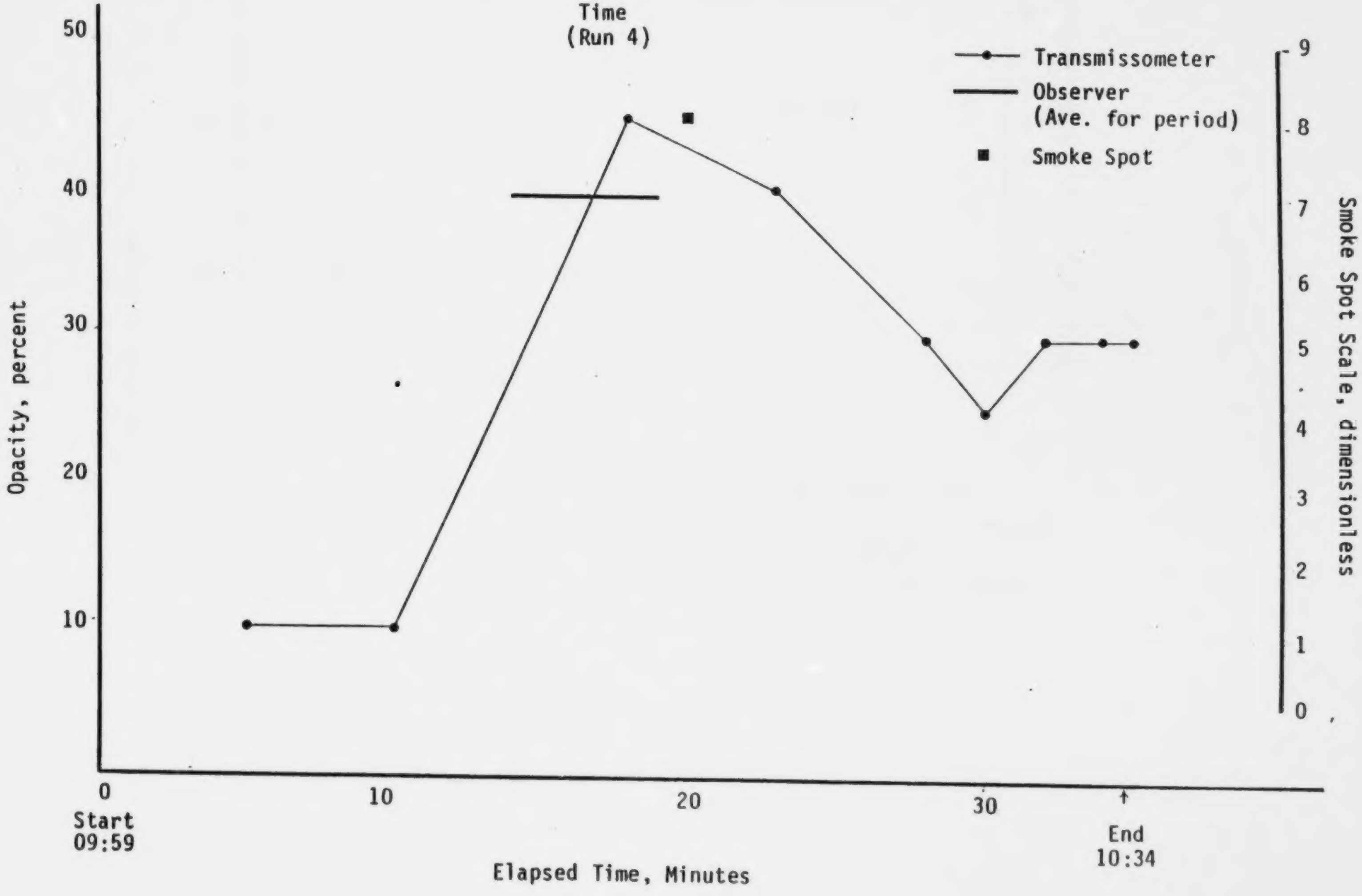


FIGURE 32

Opacity and Smoke Spot Density
vs
Time
(Run 5)

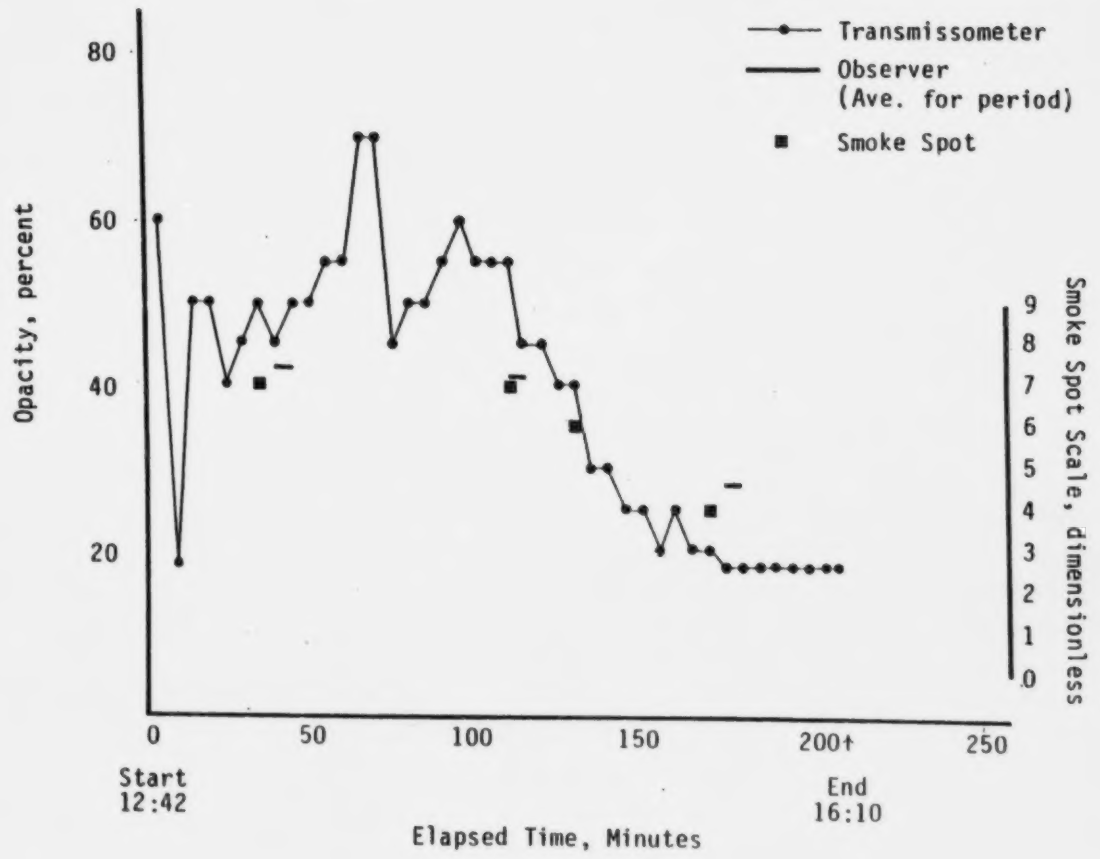


FIGURE 33

Opacity and Smoke Spot Density
vs
Time
(Run 6)

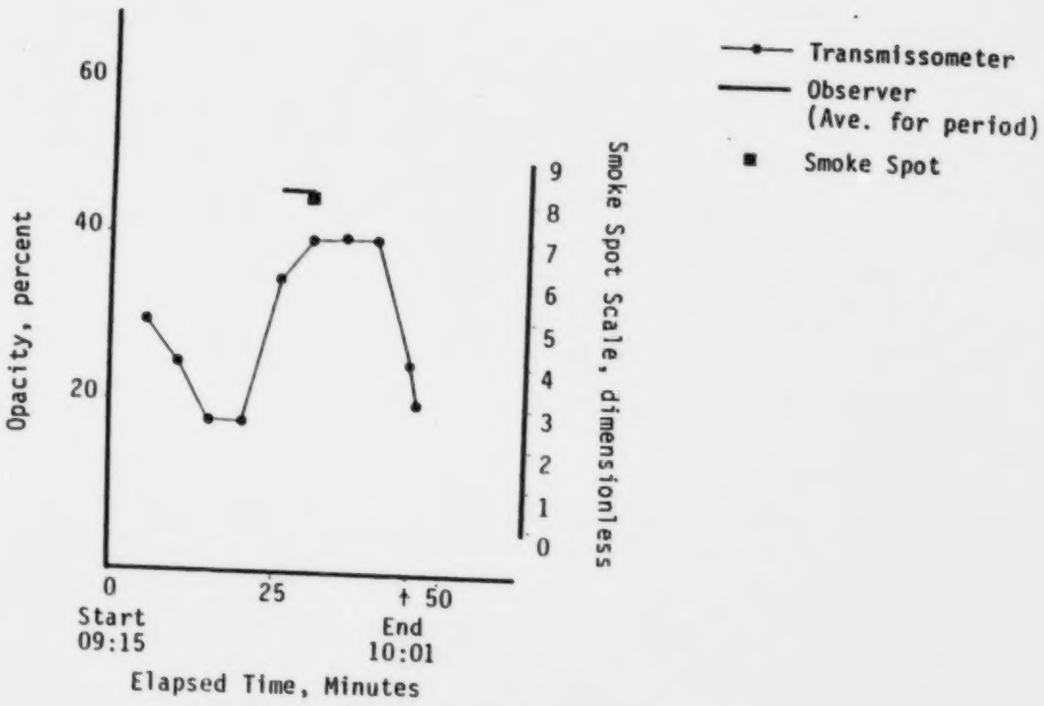


FIGURE 34

Opacity and Smoke Spot Density
vs
Time
(Run 7)

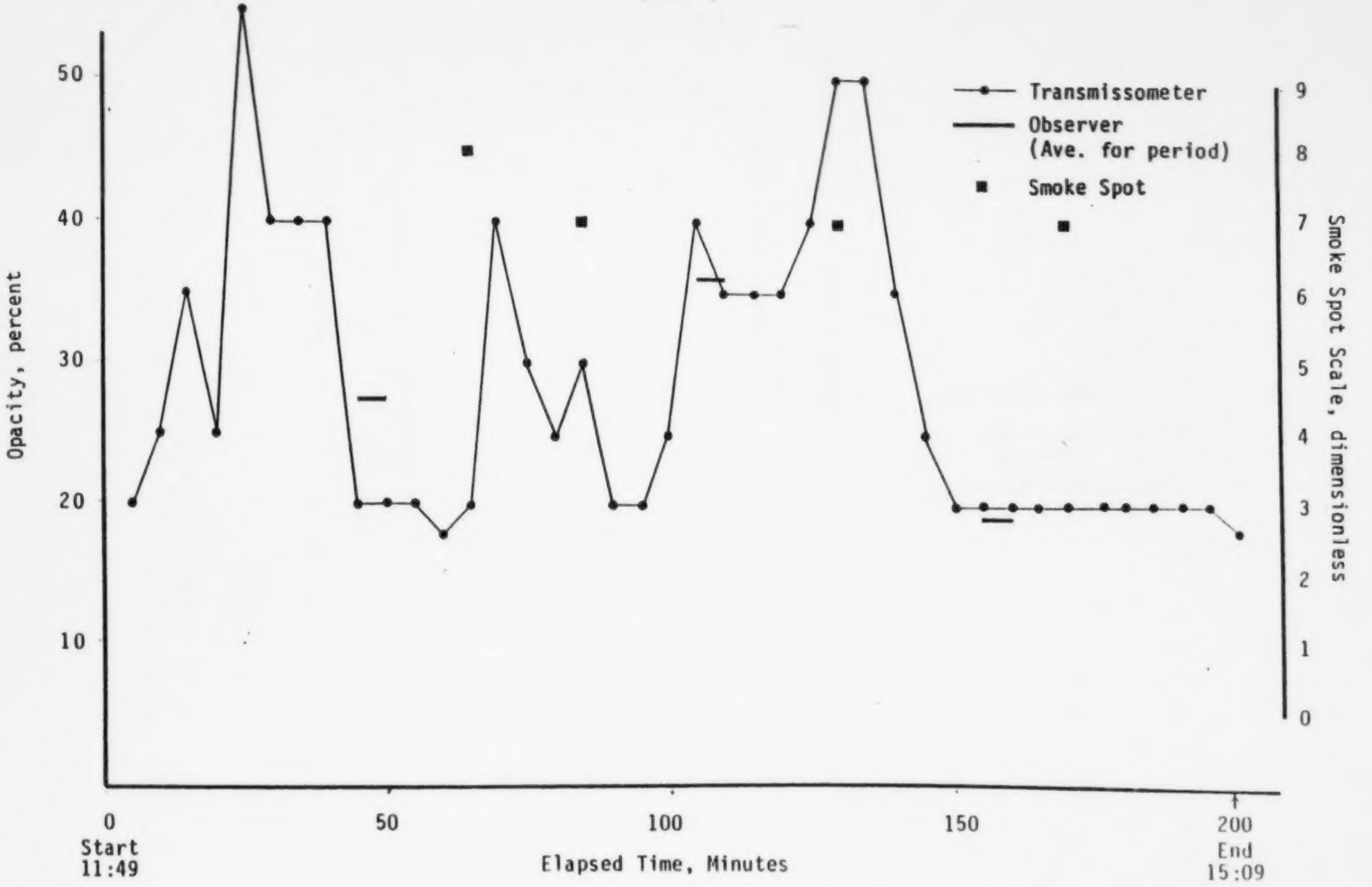


FIGURE 35

Opacity and Smoke Spot Density
vs
Time
(Run 8)

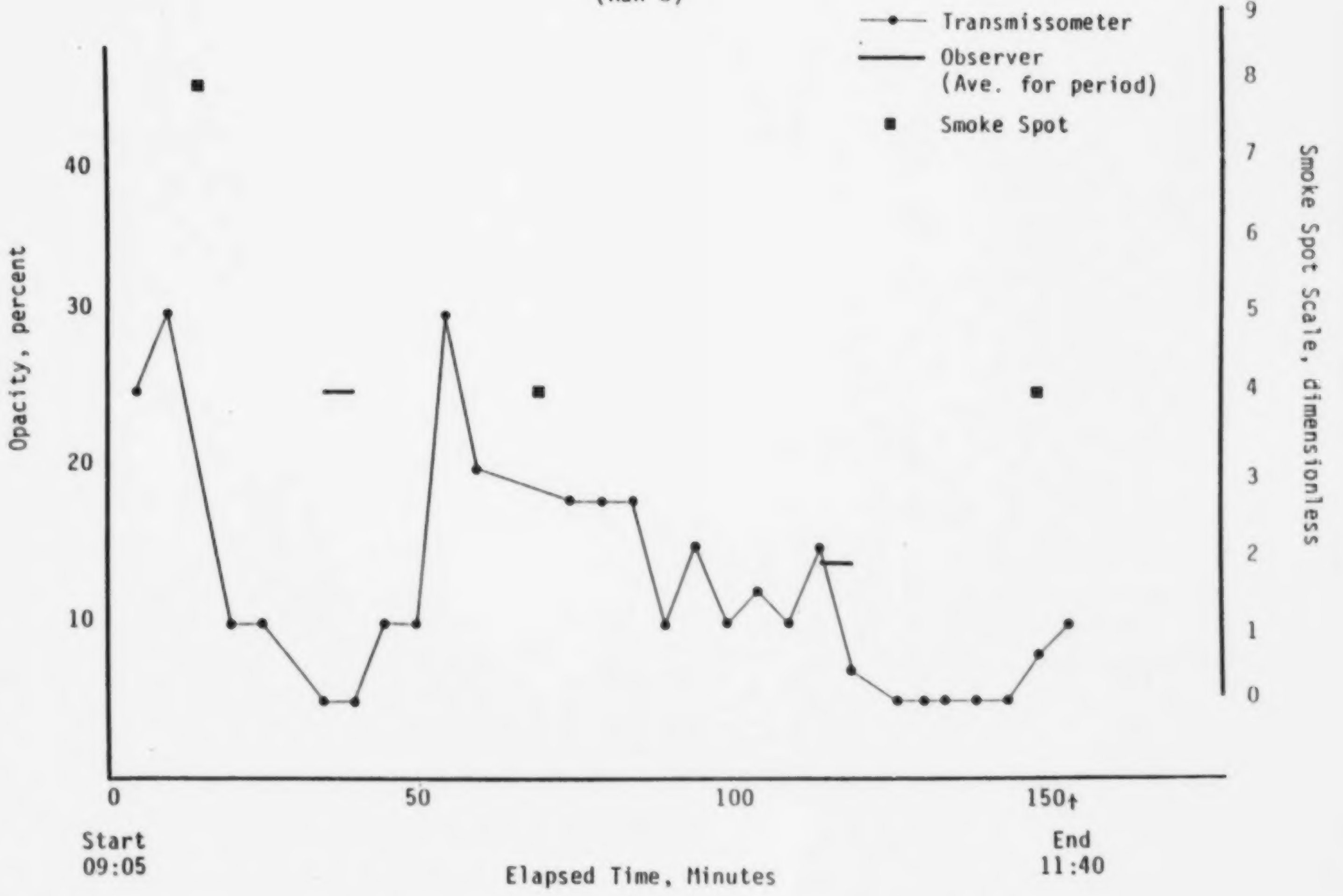


FIGURE 36

Opacity and Smoke Spot Density
vs
Time
(Run 9)

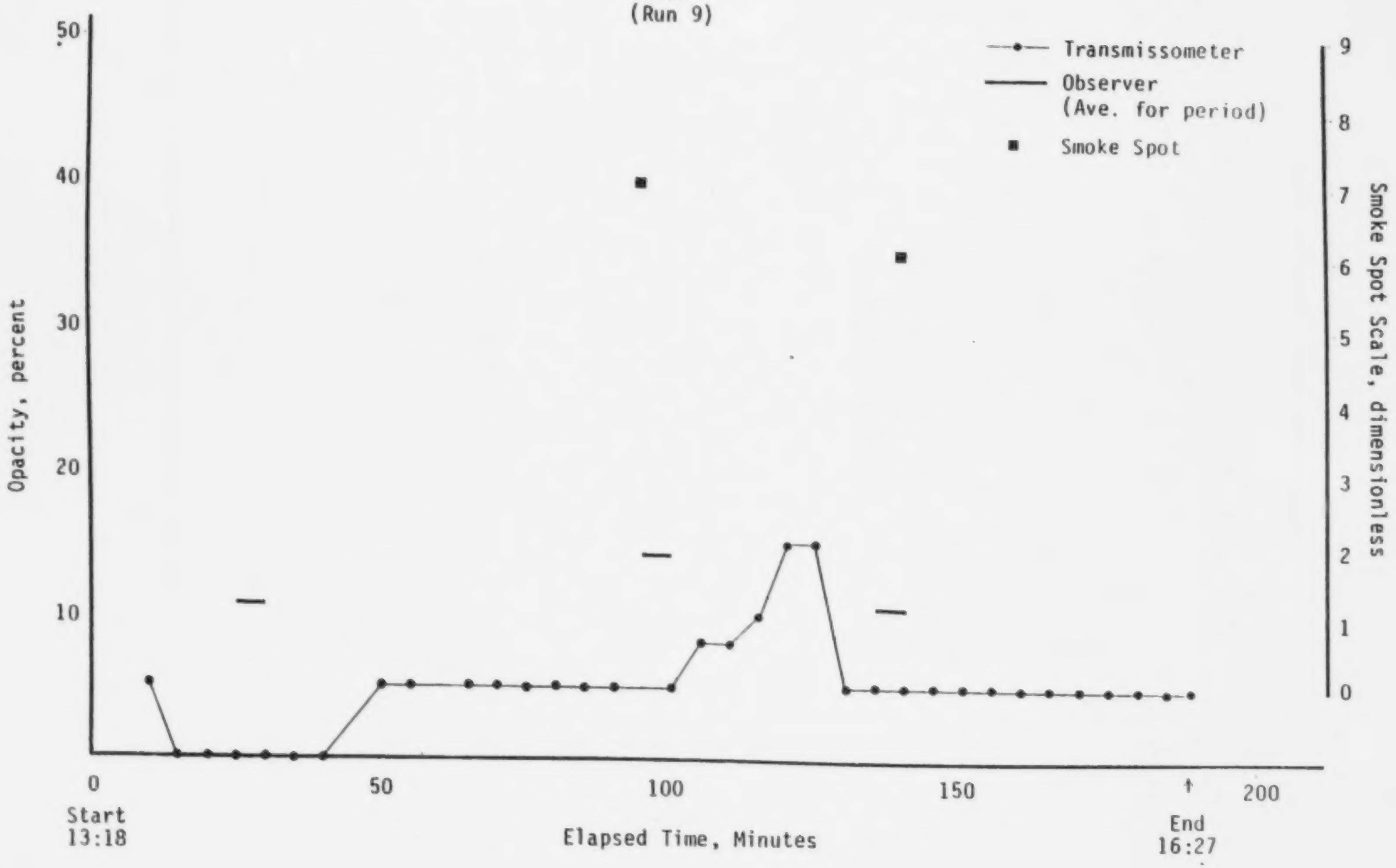


TABLE 8
Operational Log

RUN 1

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1356	26.2	483	200	Begin run; damper full open.
1401	24.8	650	270	Closed damper to 1 turn open.
1406	21.8	676	440	Closed damper 3/4 turn (1/4 open).
1431	17.5	518	415	Damper to 1/8 turn open.
1508	13.8	500	320	Phase II.
1606	9.4	478	310	Open to 1/4 turn.
1616	8.7	465	300	Open to 1/2 turn.
1641	6.5	593	350	Close to 1/4 turn open.
1740	4.1	428	300	Open damper to 1/2 turn.
1817	3.2	437	280	Open to 3/4 turn.
1833	2.5	436	295	End of burn.

TABLE 8 (Cont.)

RUN 2

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1301	27.4	--	--	Begin run; damper full open.
1305	25.8	470	400	Damper to 3/4 turn open.
1311	24.5	503	420	Damper to 1/2 turn open.
1326	20.7	579	510	Damper to 1/4 turn open at 1323.
1336	19.2	664	500	Damper to 1/8 turn open at 1333.
1342				Damper to 1/16 open.
1343	17.6	620	550	Phase II.
1351	16.2	623	540	Closed damper.
1356	15.5	540	525	Changed coupon at 1350.
1406	14.8	531	470	Open damper to 1/8 turn; closed damper at 1410.
1411	13.9	572	450	Closed damper.
1421	12.9	500	440	Open to 1/16 turn at 1420.
1516	7.2	547	430	Closed damper at 1515.

TABLE 8 (Cont.)

RUN 2 (Cont.)

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1556	4.9	574	400	Open door and poke fire.
1701	2.9	543	370	Open to 1/8 turn.
1715	2.5	541	380	End of burn.

TABLE 8 (Cont.)

RUN 3

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1234	37.2*	842	425	Begin test; dampers full open.
1243	32.8	778	470	Damper to 1/2 turn open.
1249	31.7	588	470	Damper to full turn open.
1252	31.1	676	440	Close damper to 3/4 open.
1317	25.7	517	315	Damper open to 1 turn.
1335	23.0	523	270	Damper to full open.
1338	22.2	667	290	Damper to 1 1/2 turn.
1343	20.6	550	350	Damper to 1 3/4 turn.
1355	18.5	519	340	Damper to 2 turns open.
1356				Phase II.
1400				Dampers full open.
1408	16.4	998	300	Open doors to poke fire.
1410	16.2	998	290	Close damper to 1 turn open.

* Weights include 2.7 lb tare.

TABLE 8 (Cont.)

RUN 3 (Cont.)

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1412				Open damper to 1 1/2 turn open.
1425	13.4	953	320	Close damper to 1 turn open.
1440	10.3	713	400	Close damper to 3/4 turn open.
1530	5.6	526	335	Open damper to full open.
1532				Close damper to 1 1/2 turn open.
1545	4.8	702	350	End of burn.

TABLE 8 (Cont.)

RUN 4

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
0959	29.7	-0-	-0-	Begin run.
1001		869	220	Doors closed; dampers full open.
1008		810	608	Closed dampers to 1/2 turn open.
1022	19.8	575	625	Closed damper to 1/4 turn open.
1034	17.9	703	625	End of burn.

TABLE 8 (Cont.)

RUN 5

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1242	28.6	--	--	Begin run.
1243		447	390	Doors closed; damper 1 turn open.
1252	25.2	721	480	Closed damper to 1/2 turn open.
1307	21.3	563	575	Closed to 1/4 turn open at 1305.
1353	14.8	518	450	Open damper to 1/2 open.
1358	13.9	570	500	Close damper to 1/4 turn open.
1611	4.8	520	400	End of burn.

TABLE 8 (Cont.)

RUN 6

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
0915	27.3	--	--	Begin test.
0916				Doors closed; damper full open.
0920	23.1	796	200	Close damper to 1/2 turn open.
0925	22.0	535	320	Open damper to 1 turn open.
0930	20.7	659	400	Closed damper to 3/4 open.
0935	19.5	716	440	Closed damper to 1/2 open.
0940	18.7	525	450	Opened damper to 5/8 open.
0955	16.2	514	410	Opened damper to 7/8.
1001	15.2	569	410	End of burn.

TABLE 8 (Cont.)

RUN 7

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1149	28.3	--	--	Begin run.
1154	27.0	648	430	Damper full open.
1159	25.4	594	525	Close damper to 3/4 open at 1157.
1204	24.7	550	525	Open damper to 7/8 at 1202.
1214	22.4	490	540	Open damper to 1 turn at 1217.
1219	22.0	428	470	Damper to full open.
1224	20.5	653	460	Close damper to 3/4 open at 1225.
1229	19.6	606	550	Damper to 1 turn open at 1227.
1234	18.4	735	600	Close damper to 1/2 open at 1235.
1244	16.2	750	600	Close damper to 3/8 open at 1245.
1254	14.3	677	580	Close damper to 1/4 at 1259.
1304	12.8	613	580	Open damper to 1/2 open at 1305.

TABLE 8 (Cont.)

RUN 7 (Cont.)

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1344	7.7	565	500	Open damper to 5/8 open at 1346.
1409	5.1	561	480	Open damper to 3/4 open.
1509	2.1	583	420	End of burn.

TABLE 8 (Cont.)

RUN 8

TIME	FUEL WT. (1b)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
0905	35.3	--	--	Begin run.
0910	32.1	421	120	Doors closed at 0908, damper full open.
0915	30.5	396	150	Open doors to poke at 0912.
0920	29.4	264	180	Doors opened at 0919, doors closed at 0921.
0925	29.7	748	180	Added 1.2 lb of kindling at 0924. Door closed at 0925.
0930	28.5	415	200	Added 2.8 lb of kindling at 0932, door closed at 0934.
0955	25.5	639	280	Open doors to poke fire at 0956.
1005	23.9	395	240	Open doors to poke fire at 1009.
1020	21.5	289	210	Open doors to remove coupon rod and poke the fire at 1015, closed doors at 1018.
1140	11.6	412	280	End of burn.

TABLE 8 (Cont.)

RUN 9

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1318	29.8	--	--	Begin run.
1323	27.5	902	390	Close doors at 1322.
1333	23.1	1251	525	Close dampers to 1 1/2 turn open.
1338	21.5	783	600	Open dampers to 2 turns open at 1341.
1448	10.4	490	430	Open damper to 2 1/2 turn.
1533	7.5	992	300	Open doors at 1532 to poke the fire.
1627	3.6	407	370	End of burn.

CATALYTIC RETROFIT

No major problems were encountered during Runs 10 and 11. However, there was a minor problem with grounding of the post catalyst thermocouple during both runs. For this reason the thermocouple readings that were obviously erroneous were deleted when calculating average values. Combustion temperatures during both runs averaged around 600° F. As previously mentioned, this combustion temperature is considered near the lower limit for operation of the catalytic combustor. The average temperature increase across the catalyst for Runs 10 and 11 was 125 and 290° F, respectively. The manufacturer of this unit reports that temperature increases across the catalyst of 800°F are achievable with this unit. Upon reviewing the preliminary test results, the manufacturer indicated that, in his opinion, it did not appear that proper catalytic operation had been obtained, and that this likely was due to high excess air levels causing quenching of the temperature at the catalyst. Excess air for these runs averaged 310 percent.

The average fuel consumption rate was 2.4 kg/hr. The average stove surface temperature was 385° F; the average length of the test run was 160 minutes.

TABLE 9

Results -- Catalytic Retrofit

PARAMETERS	RUN NUMBER	
	10	11
Fuel Charge (lb, Wet)	30.7	27.7
(lb, Dry)	25.1	22.5
Fuel Moisture (%, Wet)	18	19
(%, Dry)	22	23
Sample Time (Minutes)	299	223
Fuel Burned (lb, Wet)	28.1	25.6
(lb, Dry)	23.0	20.7
Burn Rate (lb/hr, Wet)	5.6	6.9
(lb/hr, Dry)	4.6	5.8
Temperatures		
Combustion (°F)	602	599
Surface (°F)	360	408
Stack (°F)	290	353
Total Particulate Emissions*		
Concentration (g/dscm)	1.26	1.34
Rate (lb/hr)	0.10	0.09
Factor (g/kg wood, Dry)	22	17
(g/10^4 Btu, Net)	16	12
Front-half (% of total)	16.6	19.7
Creosote (mg/m^2 kg)	223	190
Hydrocarbons (ppm)	125	137
Hydrocarbons (g/kg wood, Dry)	8.0	6.2
Carbon monoxide (g/kg wood, Dry)	110	90
Opacity (observer, %)	24	16
Stack Gas Composition		
CO_2 (%)	5.0	7.4
CO (%)	0.5	0.6
O_2 (%)	16.6	14.7
N_2 (%)	77.9	77.8
Moisture (%)	--	8.9
Excess Air (%)	381	240
Stack Gas Flow (dscf/hr)	1320	1130
Efficiency, (net, %)**	68	71

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* Oregon DEQ Method 7 (EPA Method 5 with back-half)

** Since techniques for determining appliance efficiency vary tremendously, the reported efficiency results should be used only as relative values for comparison between stoves and test runs under the specific operating conditions of this program.

TABLE 10

Results -- Catalytic Retrofit
(By Test Phase)

PARAMETERS	RUN NUMBER	
	10/1	10/2
Fuel Charge (lb, Wet)	30.7	
(lb, Dry)	25.1	
Fuel Moisture (%, Wet)	18	
(%, Dry)	22	
Sample Time (Minutes)	69	230
Fuel Burned (lb, Wet)	10.4	17.7
(lb, Dry)	8.5	14.0
Burn Rate (lb/hr, Wet)	9.0	4.6
(lb/hr, Dry)	7.4	3.7
Temperatures		
Combustion (°F)	687	577
Surface (°F)	445	337
Stack (°F)	345	235
Total Particulate Emissions*		
Concentration (g/dscm)	1.48	1.15
Rate (lb/hr)	0.17	0.08
Factor (g/kg wood, Dry)	24	22
(g/10^4 Btu, Net)	--	--
Front-half (% of total)	16.2	16.8
Creosote (mg/m^2 kg)	81	306
Hydrocarbons (ppm)	80	139
Hydrocarbons (g/kg wood, Dry)	4.6	9.3
Carbon monoxide (g/kg wood, Dry)	110	110
Opacity (observer, %)	22	32
Stack Gas Composition		
CO_2 (%)	5.7	4.8
CO (%)	0.6	0.5
O_2 (%)	16.8	16.3
N_2 (%)	76.9	78.4
Moisture (%)	13.4	6.4
Excess Air (%)	432	349
Stack Gas Flow (dscf/hr)	1890	1150
Efficiency, (net, %)	--	--

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* Oregon DEQ Method 7 (EPA Method 5 with back-half)

TABLE 11

Bacharach Smoke Spot Results

RUN	SAMPLE TIME	SPOT DENSITY	
		Sample Location	
		Sampling	Outlet
10 1050-1554	1155 - 1200	7	7
	1257 - 1259	5	5
	1336 - 1339	7	7
	1412 - 1415	6	6
	1459 - 1502	3	2
	Ave. Temperature	175° F	162° F
11 1057-1440	1133 - 1145	7	7
	1207 - 1213	--	6
	1245 - 1250	6	6
	1338 - 1343	5	5
	1440 - 1442	7	6
	Ave. Temperature	295° F	155° F

TABLE 12

Visible Emissions Observation Log

RUN	RUN TIME		VISIBLE EMISSIONS MEASUREMENT				
	Clock • Phase 1 • Phase 2	Elasped Min. • Phase 1 • Phase 2	Time Period	Minutes Observed	Opacity (Percent)	Opacity Range (Percent)	Average Opacity (Percent) Phases 1,2,total
10	1050 - 1159	69	1055 - 1124	30	22	10 - 40	21
	1204 - 1554	230	1125 - 1154	30	20	15 - 25	32
		299	1204 - 1213	10	32	25 - 40	23
11	1057 - 1440	223	1055 - 1104	10	9	0 - 20	16
			1210 - 1219	10	25	15 - 30	
			1300 - 1309	10	16	10 - 20	
			1400 - 1414	15	16	15 - 20	
			1440 - 1444	15	15	10 - 15	

TABLE 13

CATALYST TEMPERATURES

RUN 10

TIME Clock	/ Elapsed		TEMPERATURE, °F precatalyst (combustion)	post-catalyst
1055	05		---	810
1100	10		---	984
1110	15		---	820
1120	30		590	714
1130	40		567	723
1140	50		553	618
1210	80		527	611
1225	95		520	627
1240	110		522	597
1300	130		---	536
1320	150		---	565
1340	170		---	584
1400	190		---	704
1420	210		593	624
1440	230		498	538
1500	250		477	540
1545	295		473	558
		Average Value	532	656

Average ΔT across catalyst 125°F.

TABLE 13 (Cont.)

CATALYST TEMPERATURES

RUN 11

TIME			TEMPERATURE, °F	
Clock	/ Elapsed		precatalyst (combustion)	post-catalyst
1102	05		---	1120
1107	10		733	1036
1122	25		640	965
1137	40		517	921
1152	55		520	930
1202	65		465	---
1212	75		---	825
1227	90		580	850
1242	105		637	747
1302	125		608	894
1317	140		533	781
1332	155		498	777
1402	185		---	830
1422	205		---	660
1442	225		---	748
		Average Value	573	863

Average ΔT across catalyst 290°F.

FIGURE 37

Run 10

Gaseous Component

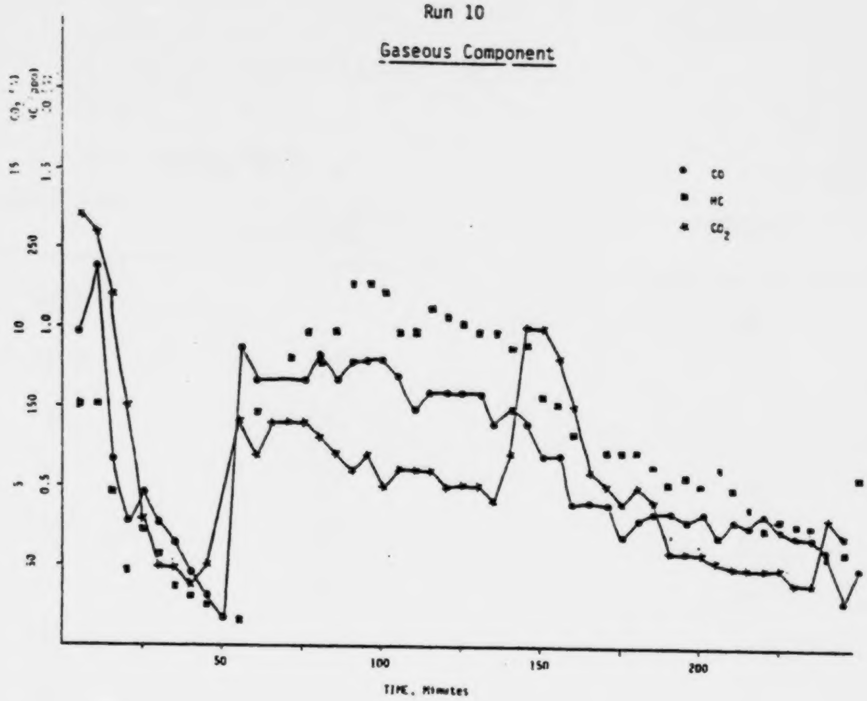


FIGURE 38

Run 10

Temperature

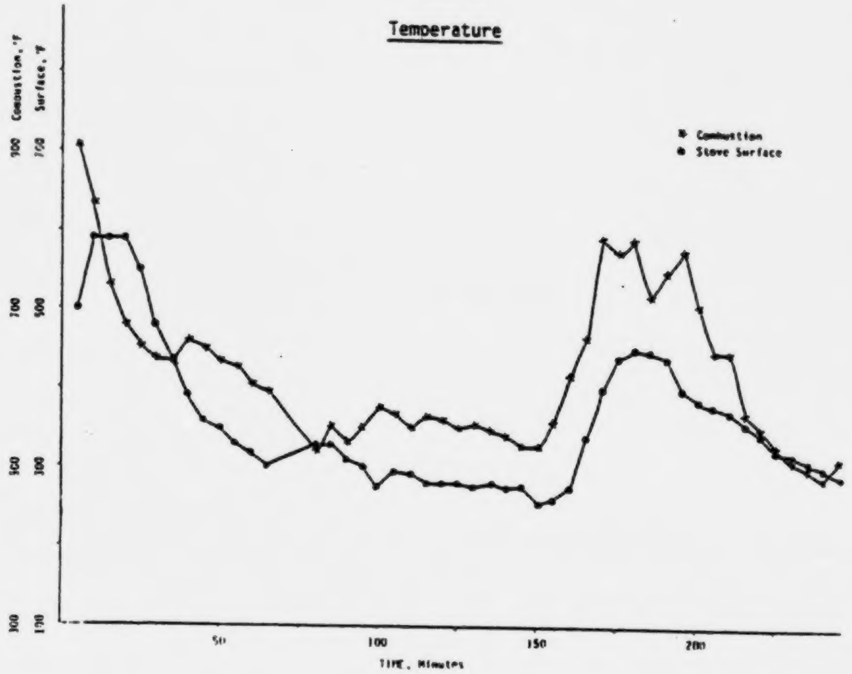


FIGURE 39

Run 11

Gaseous Component

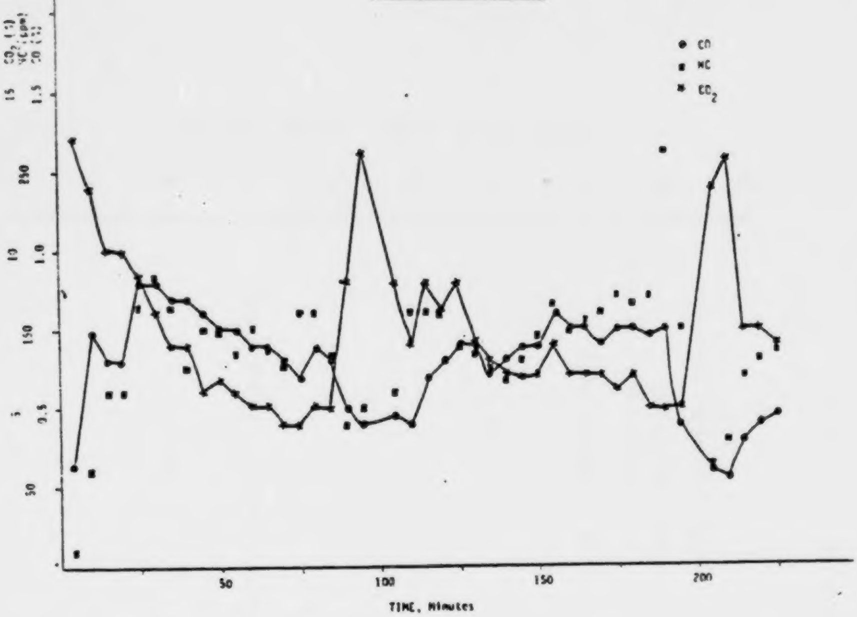


FIGURE 40

Run 11

Temperature

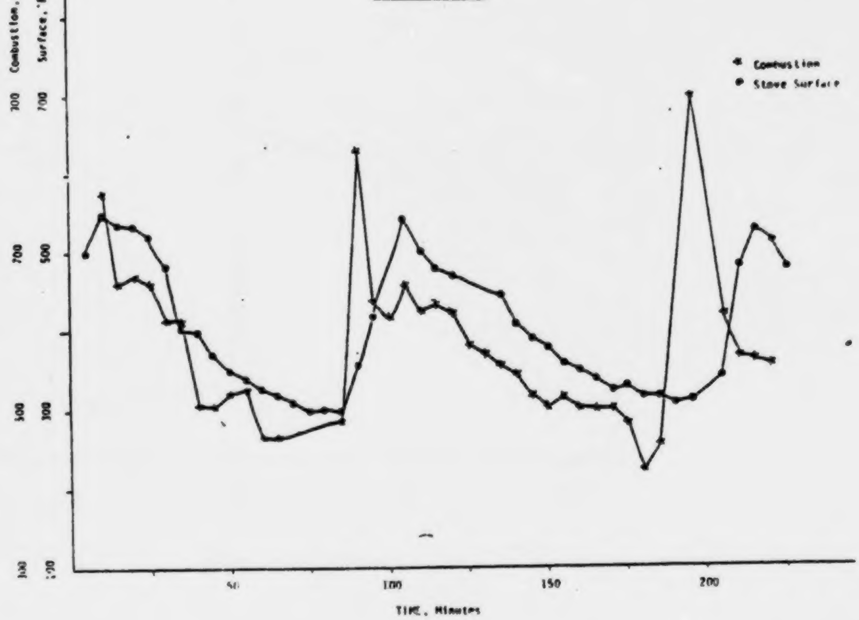


FIGURE 41

Opacity and Smoke Spot Density
vs
Time
(Run 10)

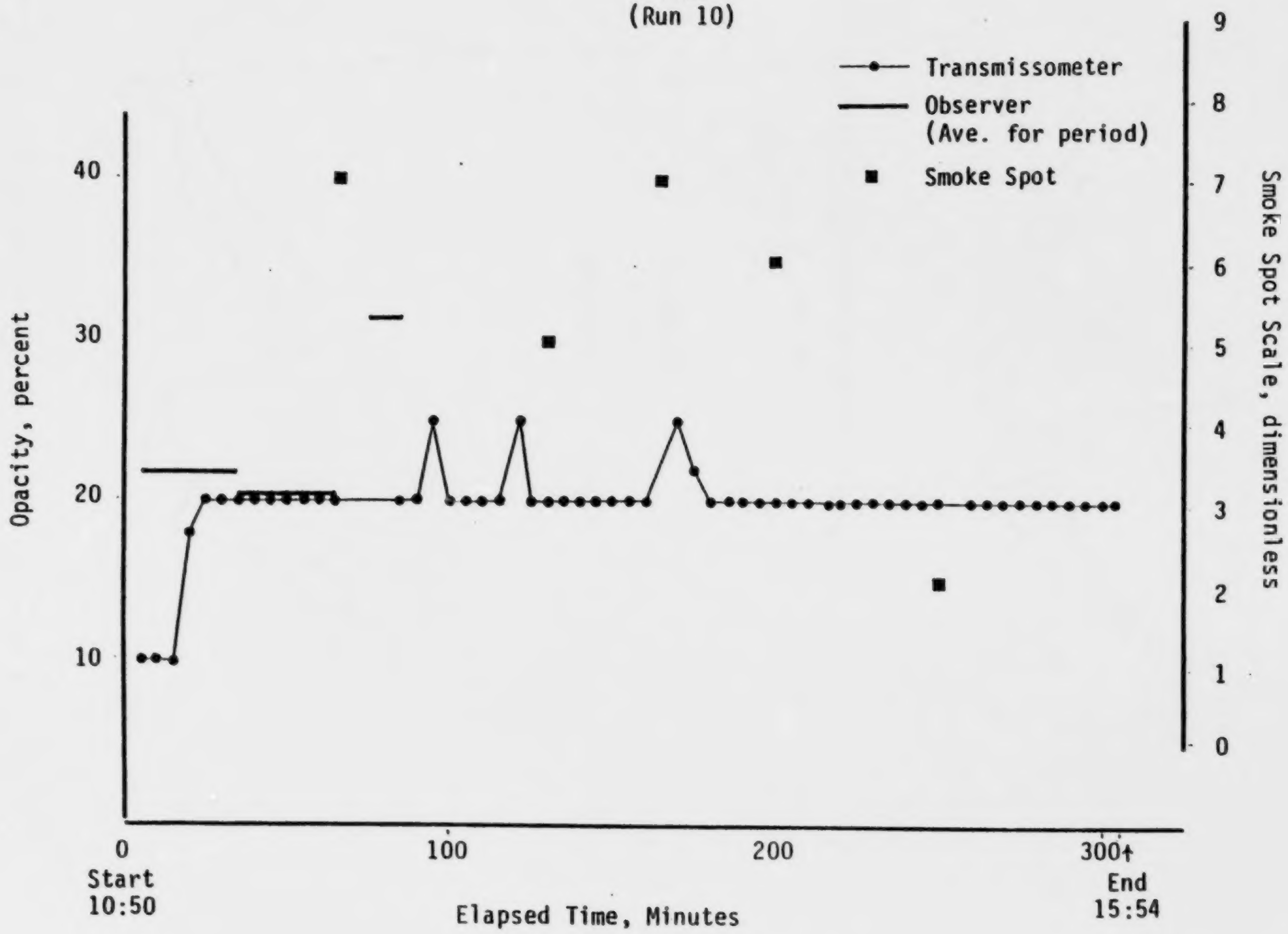


FIGURE 42

Opacity and Smoke Spot Density
vs
Time
(Run 11)

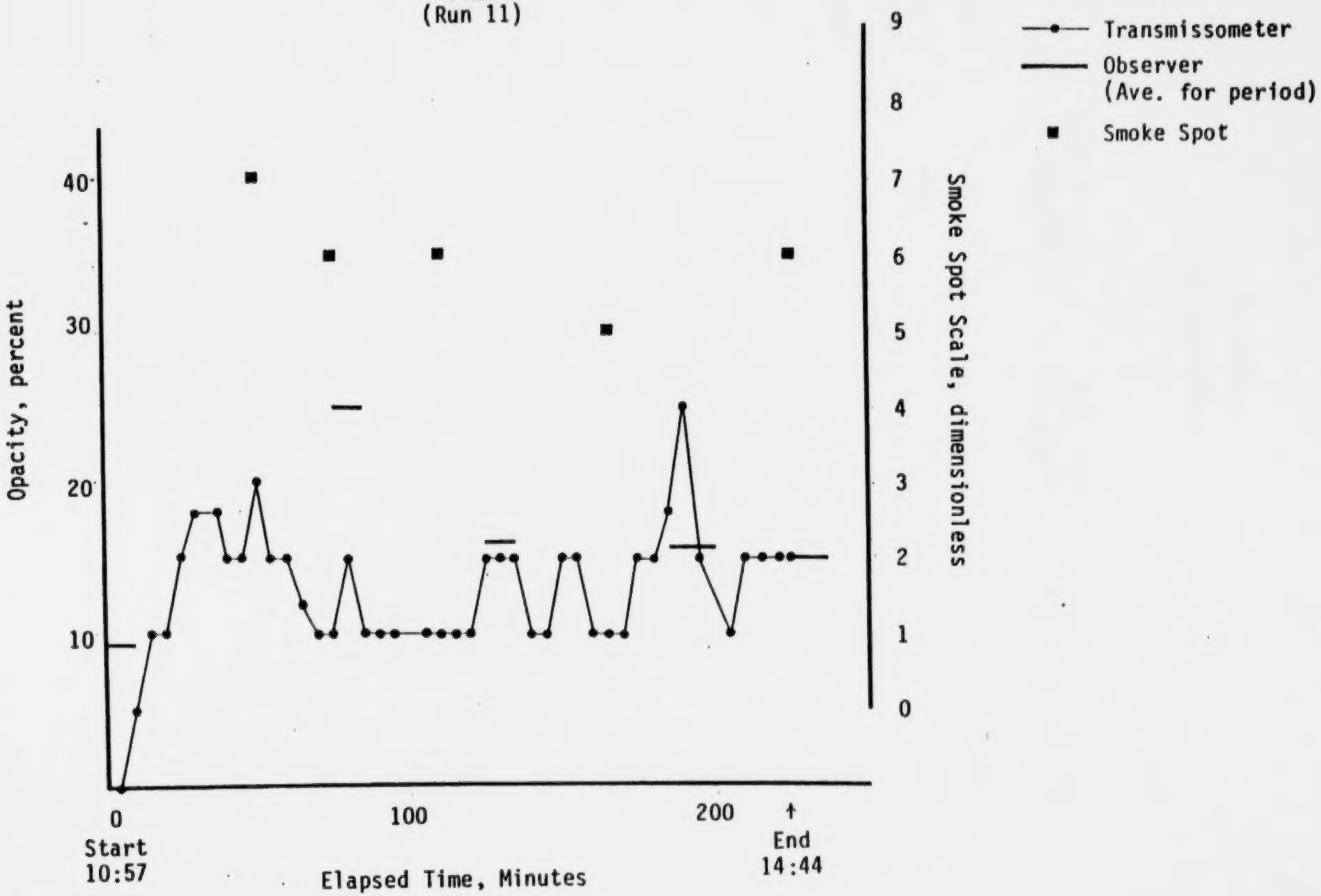


TABLE 14

OPERATION LOG

RUN 10

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1050	30.7	---	---	Doors opened, begin run..
1055	29.5	911	500	Closed doors, damper opened at 1053.
1105	26.4	733	590	Damper to 1/2 open at 1105.
1110	25.3	687	590	Damper to 1/4 open at 1112.
1120	23.8	639	480	Secondary air control off.
1125	23.1	637	440	Secondary air control on.
1130	22.7	667	390	Secondary air control off.
1135	22.2	655	360	Secondary air control on.
1155	20.3	608	300	Opened damper to 1/2 open, end of Phase I.
1220	17.8	538	310	Opened damper to 3/4 open.
1240	15.9	554	295	Secondary air control off.
1250	14.9	559	280	Secondary air control on.
1255	14.5	549	280	Dampers to 1 turn open.
1313				Doors open, fire stoked.
1315	12.9	534	275	Dampers to 1 1/2 turn open.

TABLE 14 (Cont.)

RUN 10 Cont.

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1345	9.6	789	400	Dampers to 1 turn open at 1340.
1355	8.2	792	450	Closed dampers to 3/4 turn open.
1415	6.8	708	390	Closed damper to 1/2 turn open at 1400.
1425	6.0	659	370	Closed damper to 1/4 open.
1455	5.1	488	300	Open damper to 1/2 turn open at 1455.
1510	4.6	443	280	Damper to 1 1/2 turn open at 1508.
1520	3.9	570	350	Damper to 1 turn open at 1518.
1545	2.8	490	380	Dampers to 1 1/8 turn open at 1546.
1550	2.7	480	360	Damper to 1 1/2 turn open at 1551.
1554	2.6	---	---	End of Burn.

Note: Stack damper fully open during entire run.

TABLE 14 (Cont.)

RUN 11

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (F)	STOVE SURFACE TEMPERATURE (F)	COMMENTS
1057	27.7			Begin Run.
1100		---	---	Doors closed at 1100, dampers opened; catalyst by-pass closed.
1102	25.2	1153	500	Dampers to 1 turn open at 1102.
1107	25.0	776	550	Dampers to 1/2 turn open at 1107.
1143	19.5	507	370	Opened dampers to 3/4 turn open at 1143.
1157	17.9	465	330	Open damper to 1 turn open at 1158.
1202	17.1	465	320	Removed Post catalyst TC wire and re-twisted end.
1212	15.8	504	300	Opened damper to 1 1/2 turn open at 1213.
1222	14.9	486	300	Opened damper to 2 turns open at 1224.
1227	14.7	553	360	Damper to 1 1/2 turn open at 1229.
1232	14.2	830	420	Closed damper to 1 1/4 turn at 1234. Changed filters.
1247	11.1	620	540	Closed damper to 1 turn open at 1251.
1257	9.5	627	490	Closed damper to 3/4 turn open at 1301.
1402	5.3	485	320	Opened damper to 1 turn at 1403.

TABLE 14 (Cont.)

RUN 11 Cont.

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1407	4.9	425	310	Opened damper to 1 1/2 turn.
1422				Fire stoked.
1427	3.1	1120	480	Opened damper to 3/4 turn at 1429.
1442	2.1	562	480	End of Burn at 1444.

NON-CATALYTIC RETROFIT

Runs 12 and 13 were conducted with the airtight box stove fitted with a non-catalytic retrofit device. The first run with this device was conducted on 8/27/81; prior to this run, the steel mesh in the device was cleaned and tared. After completing the emission test run on 8/27/81, stove operation was continued in order to determine if residue would build up on the mesh and cause operational problems. The stove also was operated on 8/28/81 and 8/31/81 prior to the second emission test on 9/01/81. The steel mesh pad was reweighed after the second emission test on 9/01/81. A total increase of only 2.8 grams over the original tare weight was measured.

During Run 12, the pump on the O_2 meter malfunctioned; therefore, orsat oxygen data were used for this test. A new pump was added to the system prior to Run 13. No other anomalies were noted for these test runs.

The average burn rate for the two runs was 2.9 kg/hr. Average combustion chamber and stove surface temperatures were 565 and 365° F, respectively. Excess air for the two runs averaged 300 percent. The average length of the test burn was 260 minutes.

TABLE 15

Results -- Non-catalytic Retrofit

	RUN NUMBER	
	12	13
Fuel Charge (lb, Wet)	30.8	29.2
(lb, Dry)	24.8	23.8
Fuel Moisture (%, Wet)	19	19
(%, Dry)	24	23
Sample Time (Minutes)	255	270
Fuel Burned (lb, Wet)	28.5	27.0
(lb, Dry)	23.1	21.9
Burn Rate (lb/hr, Wet)	6.7	6.0
(lb/hr, Dry)	5.4	4.9
Temperatures		
Combustion (°F)	574	553
Surface (°F)	352	381
Stack (°F)	265	251
Total Particulate Emissions *		
Concentration (g/dscm)	1.76	1.84
Rate (lb/hr)	0.21	0.17
Factor (g/kg wood, Dry)	38	35
(g/10^4 Btu, Net)	32	27
Front-half (% of total)	19.6	17.3
Creosote (mg/m^2 kg)	273	337
Hydrocarbons (ppm)	152	136
Hydrocarbons (g/kg wood, Dry)	11.8	9.3
Carbon monoxide (g/kg wood, Dry)	200	160
Opacity (observer, %)	22	23
Stack Gas Composition		
CO_2 (%)	3.7	4.1
CO (%)	0.8	0.7
O_2 (%)	16.4	15.8
N_2 (%)	79.2	79.4
Moisture (%)	8.5	--
Excess Air (%)	322	281
Stack Gas Flow (dscf/hr)	1890	1490
Efficiency, (net, %)**	60	66

---

* Oregon DEQ Method 7 (EPA Method 5 with back-half)

** Since techniques for determining appliance efficiency vary tremendously, the reported efficiency results should be used only as relative values for comparison between stoves and test runs under the specific operating conditions of this program.

TABLE 16

Results -- Non-catalytic Retrofit
(By Test Phase)

PARAMETERS	RUN NUMBER	
	13/1	13/2
Fuel Charge (lb, Wet)	29.2	
(lb, Dry)	23.8	
Fuel Moisture (%, Wet)	19	
(%, Dry)	23	
Sample Time (Minutes)	50	220
Fuel Burned (lb, Wet)	10.6	16.4
(lb, Dry)	8.6	13.3
Burn Rate (lb/hr, Wet)	12.7	4.5
(lb/hr, Dry)	10.3	3.6
Temperatures		
Combustion (°F)	589	545
Surface (°F)	419	373
Stack (°F)	275	226
Total Particulate Emissions*		
Concentration (g/dscm)	3.05	1.35
Rate (lb/hr)	0.44	0.11
Factor (g/kg wood, Dry)	42	30
($g/10^4$ Btu, Net)	--	--
Front-half (% of total)	19.3	15.9
Creosote (mg/m^2 kg)	349	329
Hydrocarbons (ppm)	169	129
Hydrocarbons (g/kg wood, Dry)	8.4	10.4
Carbon monoxide (g/kg wood, Dry)	150	180
Opacity (observer, %)	33	20
Stack Gas Composition		
CO_2 (%)	6.1	3.7
CO (%)	0.9	0.7
O_2 (%)	14.8	16.0
N_2 (%)	78.2	79.6
Moisture (%)	13.0	5.6
Excess Air (%)	228	292
Stack Gas Flow (dscf/hr)	2300	1300
Efficiency, (net, %)	--	--

---

* Oregon DEQ Method 7 (EPA Method 5 with back-half)

TABLE 17

Bacharach Smoke Spot Results

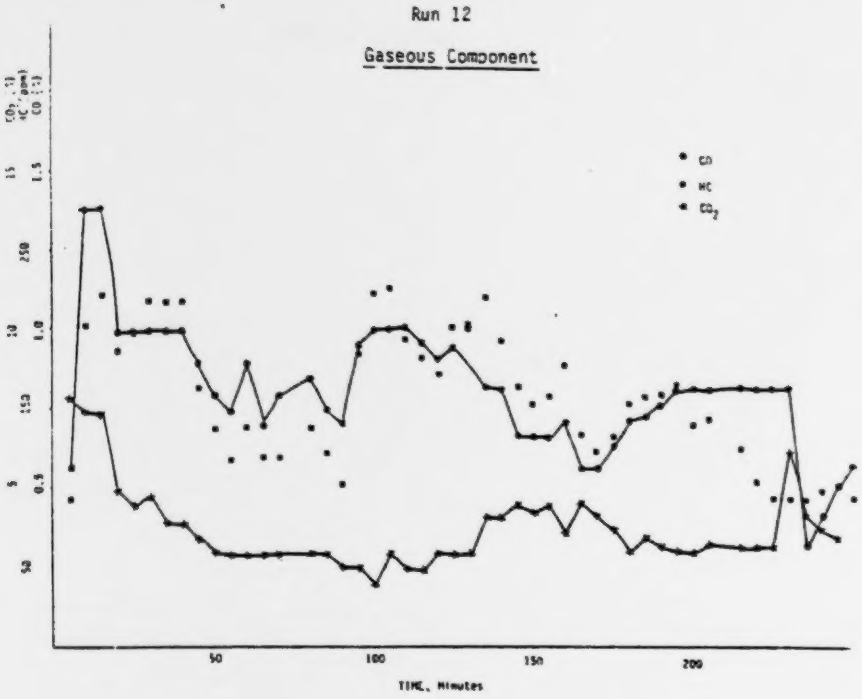
RUN	SAMPLE TIME	SPOT DENSITY	
		Sample Location	
		Sampling	Outlet
12 1020-1435	1125 - 1131	7	7
	1215 - 1233	7	7
	1249 - 1254	7	6
	1336 - 1338	7	6
	1427 - 1430	5	5
	Ave. Temperature	201° F	140° F
13 1003-1433	1030 - 1035	8	8
	1211 - 1215	7	6
	1323 - 1326	6	6
	1415 - 1418	3	2
	Ave. Temperature	269° F	134° F

TABLE 18

Visible Emission Observation Log

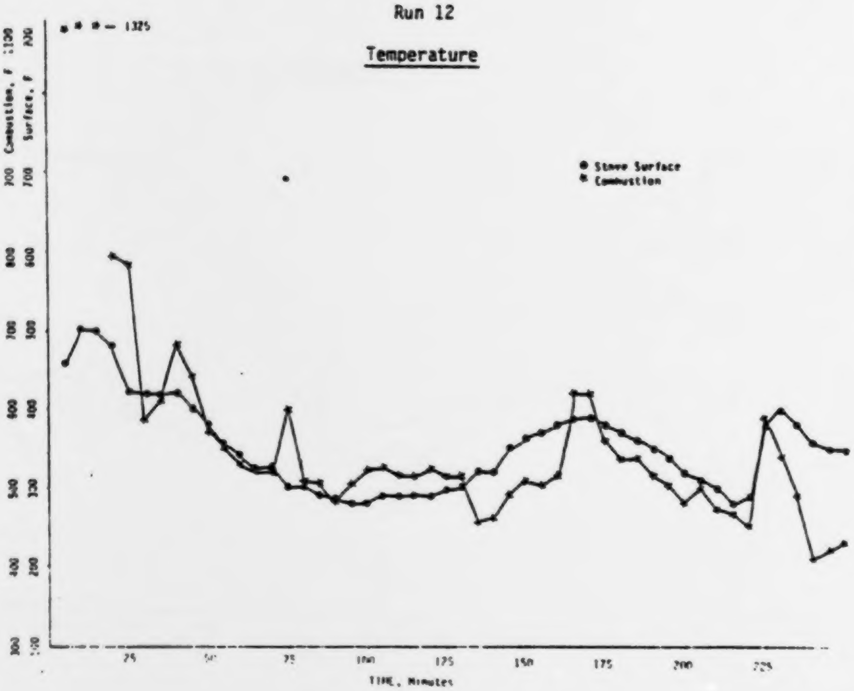
RUN	RUN TIME		VISIBLE EMISSIONS MEASUREMENT				
	Clock · Phase 1 · Phase 2	Elasped Min. · Phase 1 · Phase 2	Time Period	Minutes Observed	Opacity (Percent)	Opacity Range (Percent)	Average Opacity (Percent) Phases 1,2,total
12	1020 - 1435	255	1020 - 1029	10	25	10 - 35	22
			1110 - 1119	10	20	20 - 25	
			1215 - 1224	10	22	20 - 25	
			1310 - 1320	10	20	20	
13	1003 - 1053	50	1005 - 1015	10	33	25 - 45	33
	1053 - 1433	220	1105 - 1115	10	21	15 - 25	21
		270	1215 - 1225	10	19	15 - 25	24
			1333 - 1343	10	24	20 - 25	

FIGURE 43


Run 12

Gaseous Component

FIGURE 44


Run 12

Temperature

FIGURE 45

Run 13

Gaseous Component

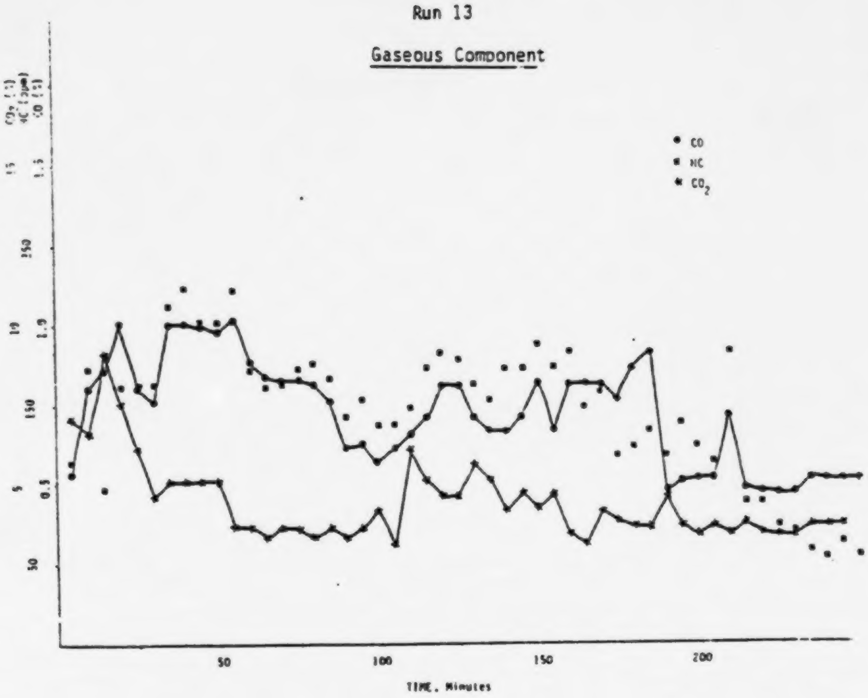


FIGURE 46

Run 13

Temperature

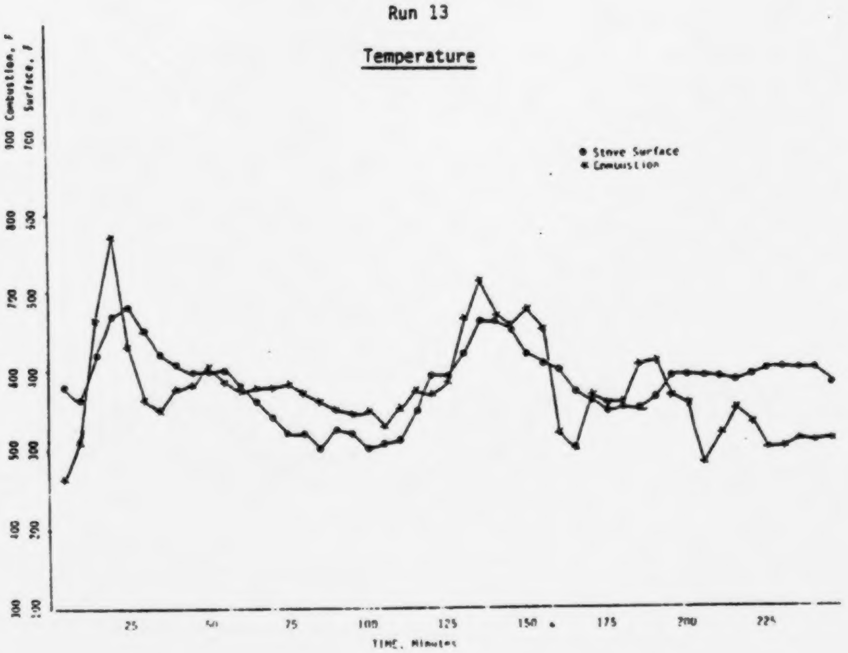


FIGURE 47

Opacity and Smoke Spot Density
vs
Time
(Run 12)

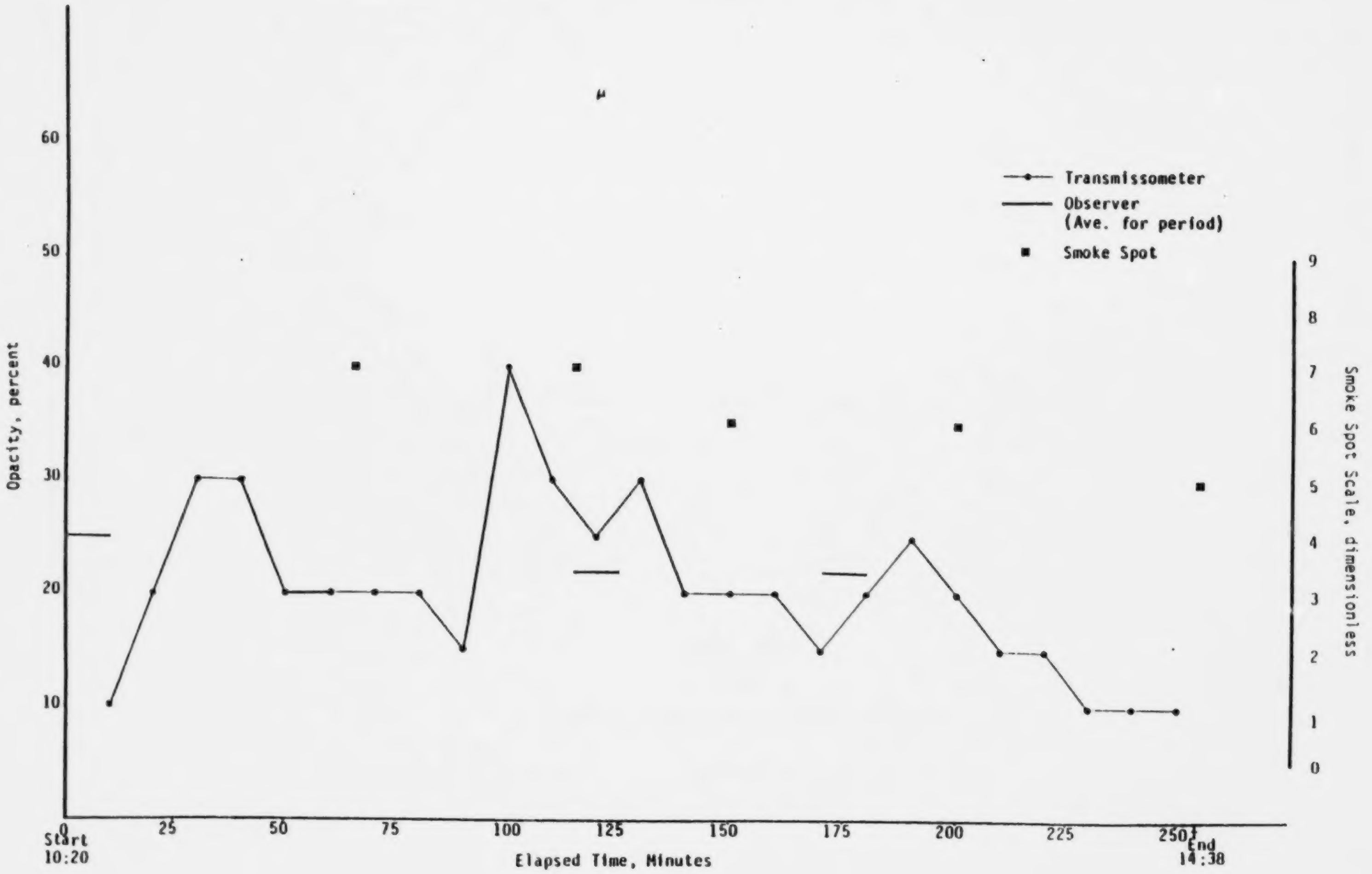


FIGURE 48

Opacity and Smoke Sopt Density
vs
Time
(Run 13)

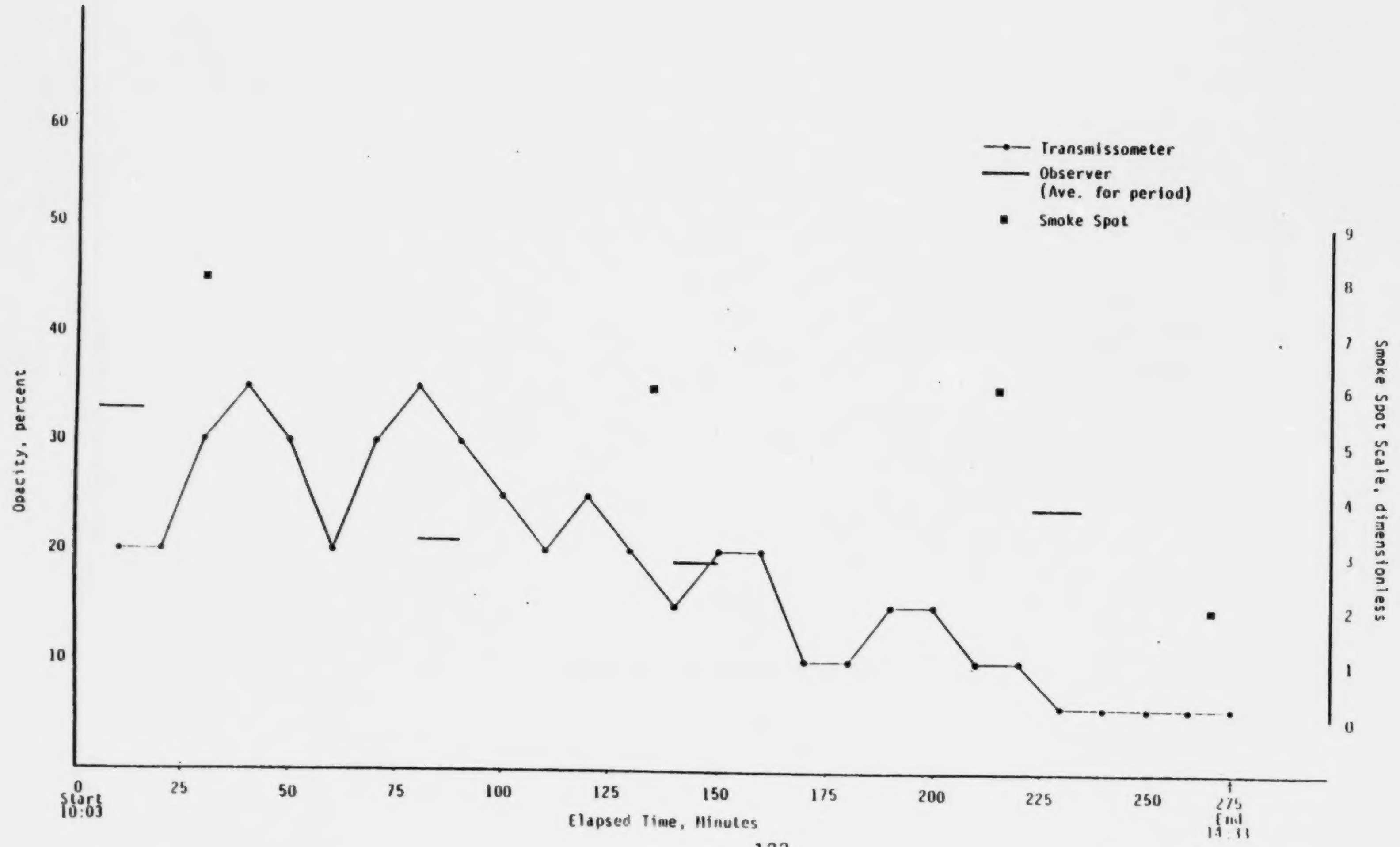


TABLE 19

Operational Log

RUN 12

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1020	30.8	--	--	Begin run.
1023				Closed doors, damper full open.
1025	28.5	1105	460	Close damper to 1 turn open at 1026.
1035	25.8	1325	500	Open damper to 1/2 turn at 1036.
1046	23.5	788	420	Open doors to remove wood from TC at 1049.
1100	21.2	681	420	Close damper to 1/4 open at 1102.
1105	20.6	643	400	Close damper to 1/8 open at 1107.
1115	19.6	551	350	Open damper to 1/4 open at 1118.
1150	16.5	481	290	Open damper to 1/2 open.
1220	13.8	524	290	Open damper to 3/4 turn open at 1218.
1235	12.3	456	300	Open damper to 1 turn open at 1237.
1240	11.8	466	320	Open damper to 1 1/2 turn open at 1241.

TABLE 19 (Cont.)

RUN 12 (Cont.)

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1305	8.8	622	380	Close damper to 1 1/4 turn open at 1307.
1340	5.6	478	340	Open damper to 2 turns open at 1348.
1410	4.1	453	280	Open doors to poke fire at 1412.
1415	3.7	592	290	Close damper to 1 turn open at 1416.
1435	2.5	413	360	Close damper to 2 turns open at 1435.
1438	2.3	427	350	End of burn at 1439.

TABLE 19 (Cont.)

RUN 13

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1003	29.2			Begin run.
1006				Doors closed; damper full open.
1018	26.0	667	420	Close damper to 1 1/2 turn open at 1020.
1023	25.1	779	470	Close damper to 1/2 turn open at 1025.
1053	18.6	595	400	Close damper to 1/4 turn open at 1054.
1058	17.6	581	400	End of Phase I.
1123	15.1	521	320	Open damper to 1/2 turn open at 1125.
1138	13.5	492	320	Open damper to 3/4 turn open at 1139.
1148	12.6	481	305	Open damper to 1 turn open at 1149.
1213	9.2	682	420	Close damper to 1/2 turn open at 1216.
1218	8.7	717	460	Close damper to 1/4 turn open at 1220.
1248	6.7	504	370	Open damper to 1/2 turn open at 1250.

TABLE 19 (Cont.)

RUN 13 (Cont.)

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1308	5.9	502	350	Open and poked fire, damper to 1 turn open at 1310.
1333	4.5	487	390	Open damper to 1 1/2 turn at 1338.
1358	3.5	500	400	Open damper to 2 turns at 1359.
1433	2.2	519	360	End of burn at 1434.

CATALYTIC BOX STOVE

No major problems were encountered with testing during Runs 14 and 15. However, problems were encountered with erratic thermocouple readings in the combustion chamber. To partially alleviate this problem, during Run 15 an additional thermocouple was placed just prior to the catalyst.

The average burn rate for the two tests was 2.0 kg/hr. Average combustion chamber and stove surface temperatures were 710 and 400°F, respectively. Excess air averaged 156 percent for the two runs; the average length of the test was 180 minutes.

Catalytic combustor operation was marginal during Run 15, as indicated by temperature change across the catalyst. During Run 15 a catalyst temperature change of only about 100°F was noted, with an average combustion chamber temperature of 800°F. For Run 14 with a significantly lower average combustion chamber temperature of only 600°F, a temperature rise of about 200°F was noted across the catalyst. During Run 14 a fairly constant glow was noted on the catalyst. Nonetheless, Run 14 had significantly higher emissions than Run 15. From these results it would appear that the higher burn rate of Run 15 (2.2 kg/hr vs 1.6 kg/hr) had a greater impact on emissions, than did catalyst operation. Note in Figure 52 how at approximately 70 minutes into test Run 15, the combustion chamber temperature was increased resulting in a significant increase in CO_2 and corresponding decrease in CO.

TABLE 20

Results -- Catalytic Box Stove

PARAMETERS	RUN NUMBER	
	14	15
Fuel Charge (lb, Wet)	16.8	16.6
(lb, Dry)	13.8	13.3
Fuel Moisture (%, Wet)	17	20
(%, Dry)	21	25
Sample Time (Minutes)	209	150
Fuel Burned (lb, Wet)	15.5	15.4
(lb, Dry)	12.9	12.3
Burn Rate (lb/hr, Wet)	4.5	6.2
(lb/hr, Dry)	3.7	4.9
Temperatures		
Combustion (°F)	609	815
Surface (°F)	382	412
Stack (°F)	244	323
Total Particulate Emissions*		
Concentration (g/dscm)	2.15	1.51
Rate (lb/hr)	0.14	0.11
Factor (g/kg wood, Dry)	38	23
($g/10^4$ Btu, Net)	28	16
Front-half (% of total)	15.6	21
Creosote (mg/m^2 kg)	379	273
Hydrocarbons (ppm)	167	134
Hydrocarbons (g/kg wood, Dry)	10.7	7.3
Carbon monoxide (g/kg wood, Dry)	120	50
Opacity (observer, %)	10	10
Stack Gas Composition		
CO_2 (%)	5.9	6.3
CO (%)	0.6	0.3
O_2 (%)	12.8	13.5
N_2 (%)	80.7	78.9
Moisture (%)	--	10.4
Excess Air (%)	140	172
Stack Gas Flow (dscf/hr)	1060	1200
Efficiency, (net, %)**	68	71

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* Oregon DEQ Method 7 (EPA Method 5 with back-half)

** Since techniques for determining appliance efficiency vary tremendously, the reported efficiency results should be used only as relative values for comparison between stoves and test runs under the specific operating conditions of this program.

TABLE 21

Results -- Catalytic Box Stove
(By Test Phase)

PARAMETERS	RUN NUMBER 14/1	RUN NUMBER 14/2
Fuel Charge (lb, Wet)	16.8	
(lb, Dry)	13.8	
Fuel Moisture (%, Wet)	17	
(%, Dry)	21	
Sample Time (Minutes)	42	167
Fuel Burned (lb, Wet)	6.7	8.8
(lb, Dry)	5.6	7.3
Burn Rate (lb/hr, Wet)	9.6	3.2
(lb/hr, Dry)	8.0	2.6
Temperatures		
Combustion (°F)	582	615
Surface (°F)	407	376
Stack (°F)	287	212
Total Particulate Emissions*		
Concentration (g/dscm)	2.14	2.15
Rate (lb/hr)	0.39	0.08
Factor (g/kg wood, Dry)	49	30
(g/10^4 Btu, Net)	--	--
Front-half (% of total)	24.7	12.2
Creosote (mg/m^2 kg)	389	371
Hydrocarbons (ppm)	102	183
Hydrocarbons (g/kg wood, Dry)	8.4	7.0
Carbon monoxide (g/kg wood, Dry)	80	110
Opacity (observer, %)	13	9
Stack Gas Composition		
CO_2 (%)	3.9	6.4
CO (%)	0.3	0.7
O_2 (%)	12.9	12.7
N_2 (%)	82.9	80.2
Moisture (%)	13.6	8.3
Excess Air (%)	140	140
Stack Gas Flow (dscf/hr)	2940	590
Efficiency, (net, %)	--	--

---

* Oregon DEQ Method 7 (EPA Method 5 with back-half)

TABLE 22

Bacharach Smoke Spot Results

RUN	SAMPLE TIME	SPOT DENSITY	
		Sample Location	
		Sampling	Outlet
14 1050-1419	1136 - 1139	7	7
	1229 - 1235	6	6
	1336 - 1339	6	4
	1412 - 1417	7	4
	Ave. Temperature	192°F	109°F
15 1035-1305	1134 - 1137	8	8
	1232 - 1238	6	4
	Ave. Temperature	321° F	145° F

TABLE 23

Visible Emission Observation Log

RUN	RUN TIME		VISIBLE EMISSIONS MEASUREMENT				
	Clock · Phase 1 · Phase 2	Elasped Min. · Phase 1 · Phase 2	Time Period	Minutes Observed	Opacity (Percent)	Opacity Range (Percent)	Average Opacity (Percent) Phases 1,2,total
14	1050 - 1232	42	1107 - 1117	10	13	10 - 20	10
	1232 - 1419	167	1143 - 1153	10	6	5 - 10	9
		209	1255 - 1265	10	17	10 - 20	10
			1415 - 1425	10	<5	<5	
15	1035 - 1305	150	1041 - 1051	10	14	5 - 25	11
			1203 - 1213	10	7	5 - 10	

TABLE 24

CATALYST TEMPERATURES

RUN 14

TIME		TEMPERATURE, °F	
Clock /	Elapsed	precatalyst (combustion)	post-catalyst
1050	0	---	---
	10	652	1102
	20	535	1032
	30	473	1002
	40	520	1131
	50	870*	1122
1150	60	738	850
	70	652	725
	80	607	711
	90	598	603
	100	567	817
	110	560	758
1250	120	640	732
	130	658	756
	140	584	767
	150	598	753
	160	589	714
	170	613	669
	180	579	655
	190	547	681

* Thermocouple repositioned.

TABLE 24 (Cont.)

CATALYST TEMPERATURES

RUN 14 Cont.

TIME			TEMPERATURE, °F	
Clock /	Elapsed		precatalyst (combustion)	post-catalyst
	200		603	623
1419	209		602	600
		Average Value	609	800

Average ΔT across catalyst 190°F.

TABLE 24 (Cont.)

CATALYST TEMPERATURES

RUN 15

TIME Clock	/ Elapsed		TEMPERATURE, °F precatalyst (combustion)	 post-catalyst
1035	0		---	---
	10		1076	993
	20		843	728
	30		401	734
	40		415	638
	50		454	909
1135	60		558	935
	70		541	801
	80		908	734
	90		996*	789
	100		922	948
	110		922	921
1235	120		---	915
	130		---	914
	140		939	893
1305	150		---	847
		Average Value	748	851

* New thermocouple added and positioned directly below catalyst; temperatures recorded in test log book, only.

Average ΔT across catalyst 100°F.

FIGURE 49

Run.14

Gaseous Component

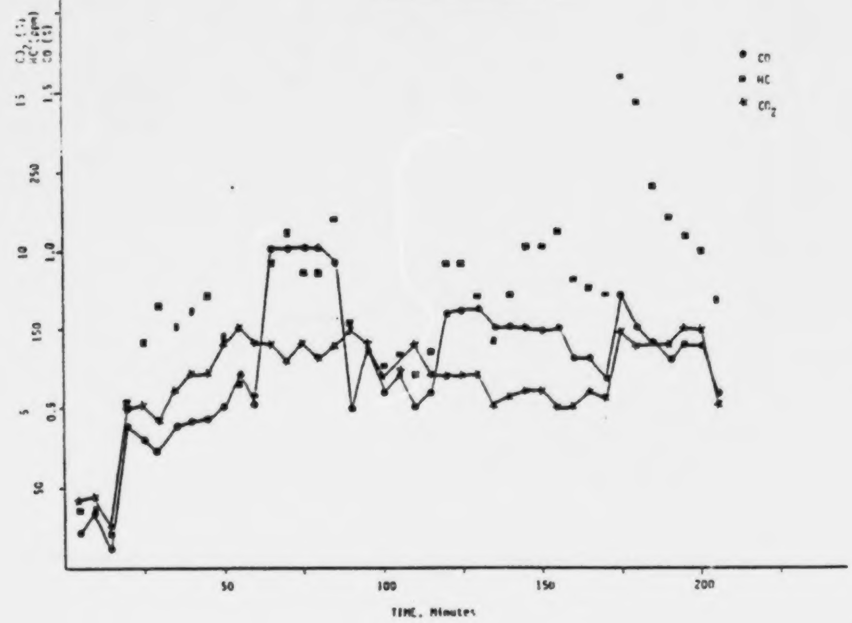


FIGURE 50

Run 14

Temperature

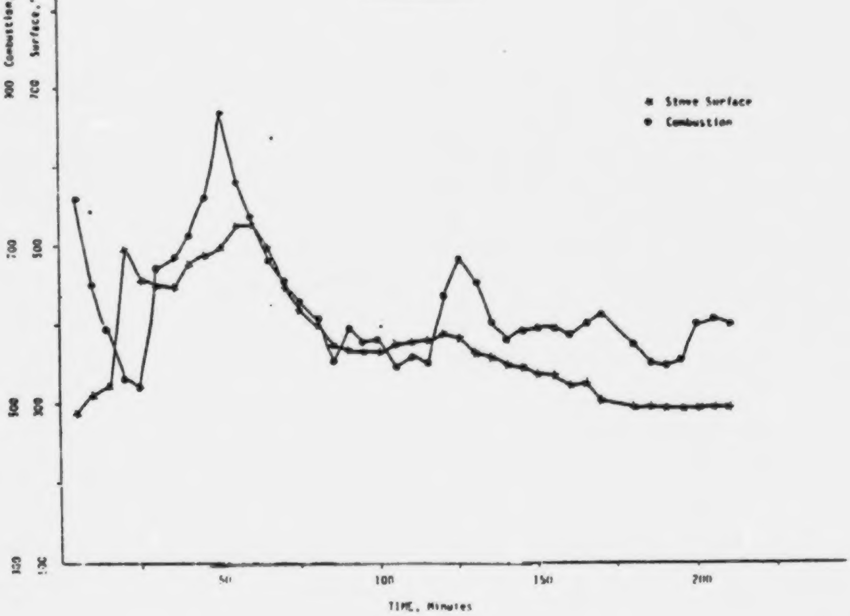
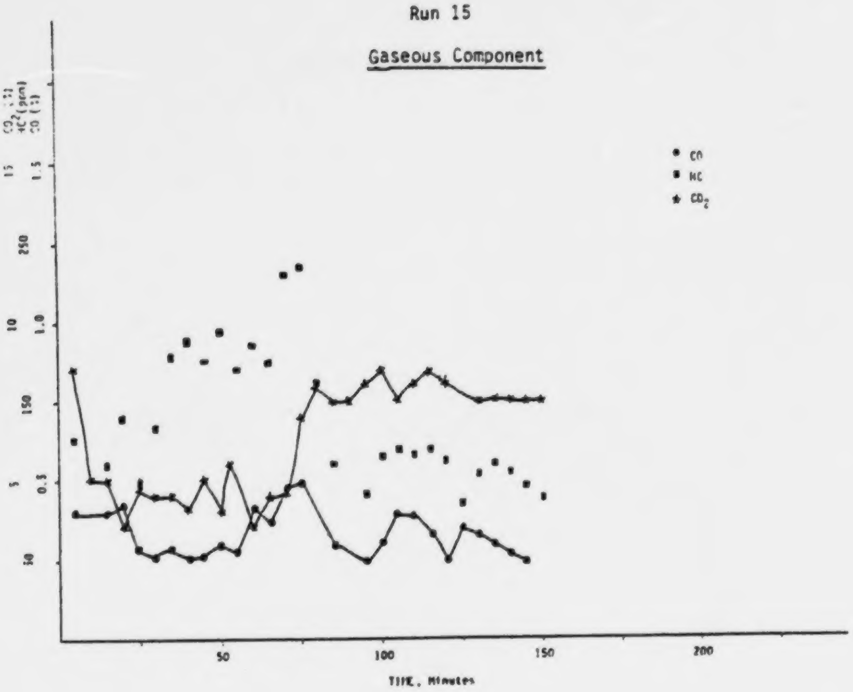


FIGURE 51

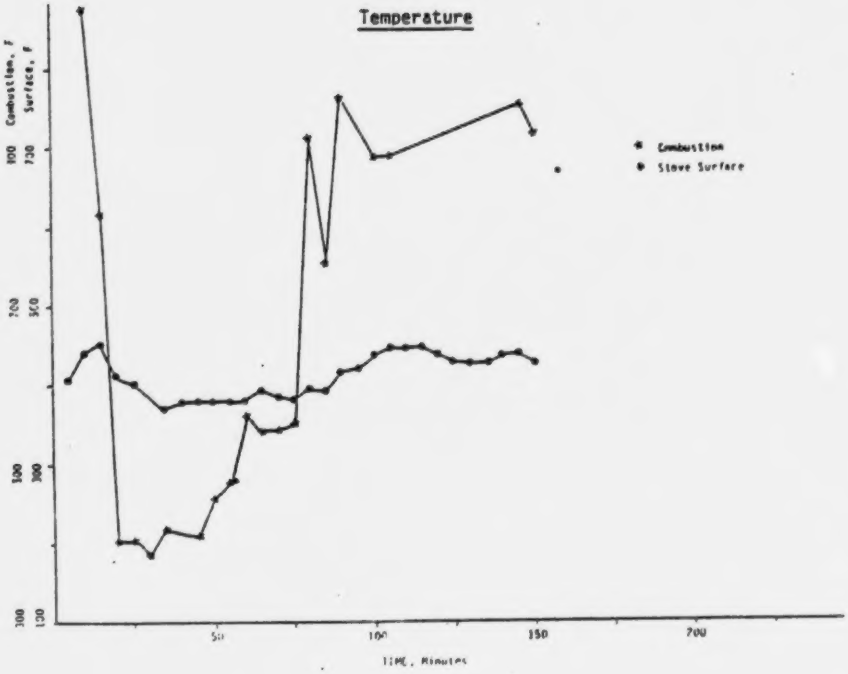
Run 15



Gaseous Component

FIGURE 52

Run 15



Temperature

FIGURE 53

Opacity and Smoke Spot Density
vs
Time
(Run 14)

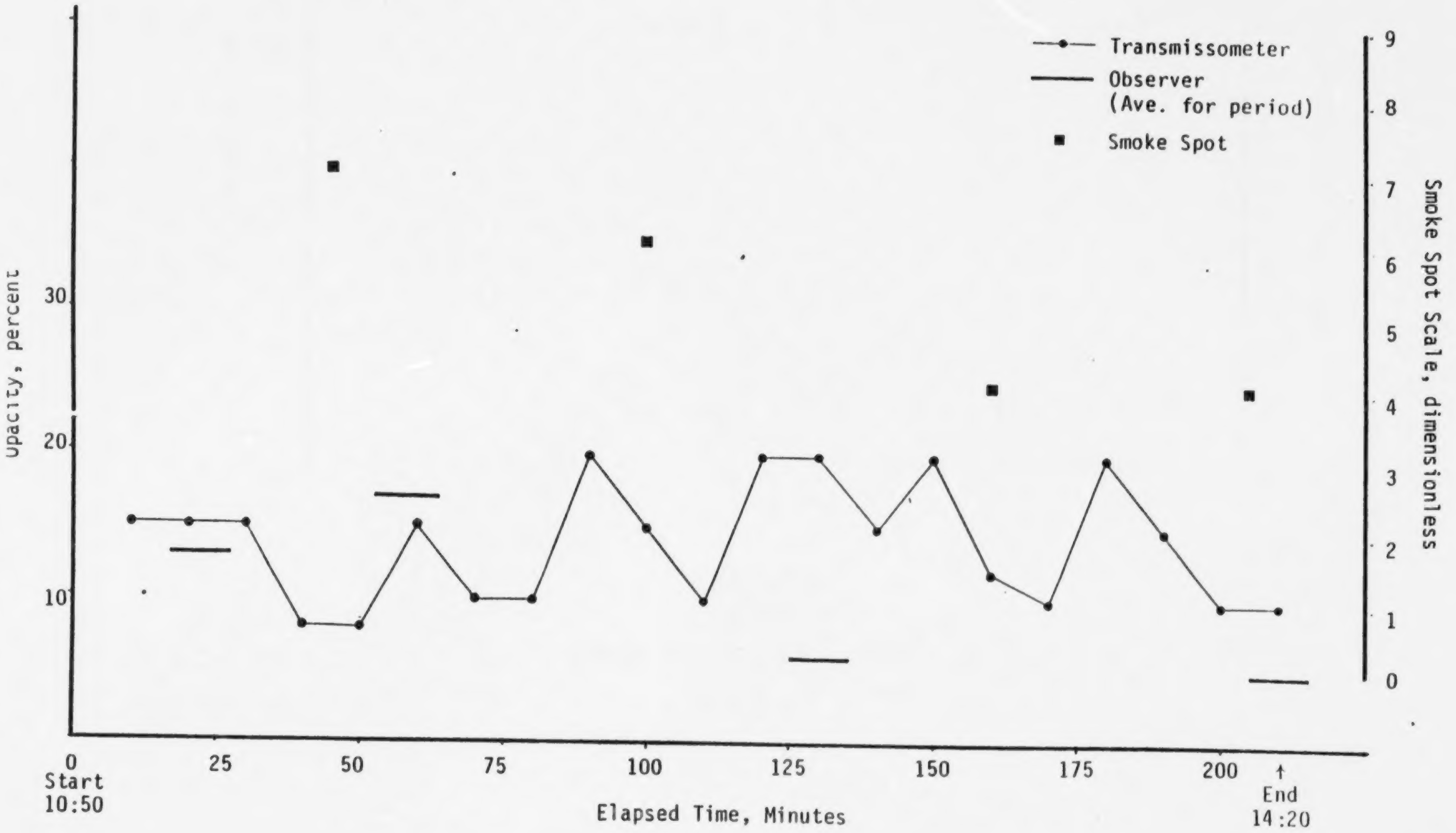


FIGURE 54

Opacity and Smoke Spot Density
vs
Time
(Run 15)

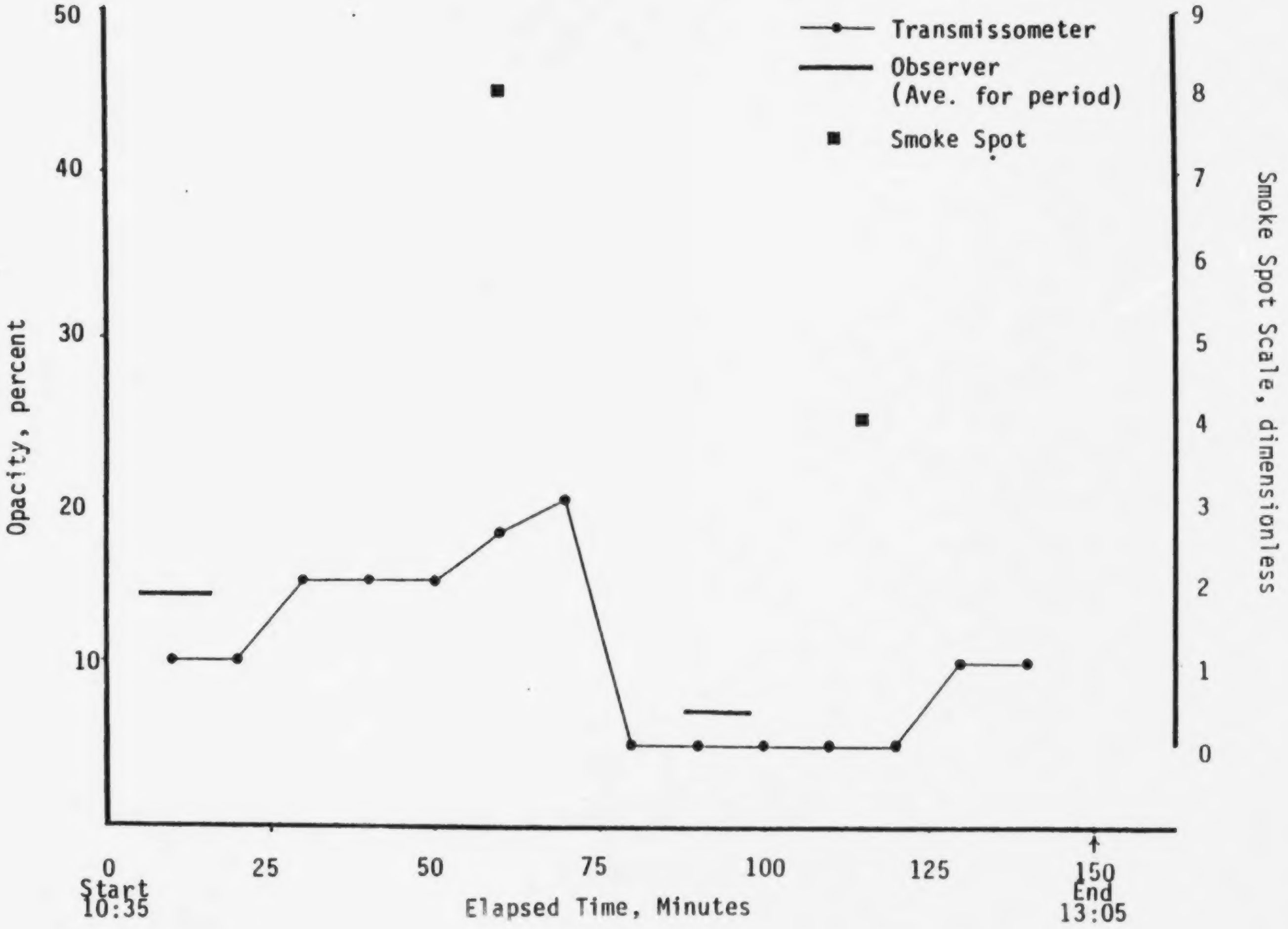


TABLE 25

OPERATION LOG

RUN 14

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1050	16.8			Begin Run.
1055	15.5	761	290	Damper to 2 turns open at 1057; catalyst glow noted.
1100	14.5	652	310	Damper to 3 turns open at 1104.
1105	13.6	600	320	Damper to 2 turns open at 1107; catalyst glow noted.
1110	12.8	535	500	Changed surface temp. reading to top of stove.
1115	12.1	526	460	Damper to 3 turns open at 1118; glow on 50% of catalyst only.
1140	8.2	870	500	Damper to 3/4 turn open at 1142.
1145	7.6	787	525	Damper to 3/4 turn open at 1147; glow on all of catalyst.
1150	6.8	738	530	Damper to 1/4 turn open at 1150; no catalyst glow.
1213				No catalyst glow.
1216	5.5	557	380	Open doors to poke the fire at 1218.
1217				Faint catalyst glow.
1231				Medium catalyst glow.
1248				Faint catalyst glow.
1335				No catalyst glow.
1340	2.4	613	310	Open doors to poke the fire at 1347.

TABLE 25 (Cont.)

RUN 15

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1035	16.6			Begin Run.
1038	---	---	---	Closed doors, damper full open at 1038; good catalyst glow.
1040	14.8	1149	410	Damper to 1 1/2 turn open at 1041.
1045	14.1	1076	430	Damper to 1/2 turn open at 1045.
1050	13.6	832	450	Damper to 1/4 turn open at 1047; faint catalyst glow.
1055	13.2	843	410	Doors opened at 1055 to poke the fire; no catalyst glow.
1100	12.8	402	400	Damper to 1 turn open at 1059.
1105	12.3	401	400	Doors opened at 1109 to look; no catalyst glow.
1110	11.9	389	370	Damper to 2 turns open at 1110.
1200	5.9	749	390	Changed M-5 filters.
1202				Moved thermocouple to directly below catalyst.
1206				Faint catalyst glow.
1211	4.7	960	420	Dampers to 1 turn open at 1213.
1220				No catalyst glow.
1255				No catalyst glow.
1305	1.2	915	430	End of Burn at 1306.

TABLE 25 (Cont.)

RUN 14 Cont.

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1410				No catalyst glow.
1419	1.3	602	290	End of Burn at 1420.

CATALYTIC MODIFIED COMBUSTION STOVE

No major problems were encountered with emission testing during Runs 16 and 17. The only testing anomaly noted is that separate creosote coupons were not used for each phase of Run 17 as per the test protocol; a single coupon at each measurement location was used for the entire run.

Regarding stove operation the burn rate for Run 16 was slightly higher than called for in the test protocol, and was significantly higher than Run 17. The burn rates for Runs 16 and 17 were 3.0 and 2.1 kg/hr, respectively. Average combustion chamber temperatures for the two runs were 630 and 490° F; this slight change in combustion temperature appears to have had a significant impact on emission levels; the measured emissions for test Run 16 were approximately one-half the measured value for Run 17 (14 vs 30 g/kg wood). Excess air for the two runs averaged 422 percent. The average length of the two tests was 150 minutes.

TABLE 26

Results -- Catalytic Modified Combustion Stove

PARAMETERS	RUN NUMBER 16	RUN NUMBER 17
Fuel Charge (lb, Wet)	17.6	18.7
(lb, Dry)	14.2	15.0
Fuel Moisture (%, Wet)	19	20
(%, Dry)	24	25
Sample Time (Minutes)	120	175
Fuel Burned (lb, Wet)	16.4	17.3
(lb, Dry)	13.3	13.8
Burn Rate (lb/hr, Wet)	8.2	5.9
(lb/hr, Dry)	6.7	4.7
Temperatures		
Combustion (°F)	627	491
Surface (°F)	354	259
Stack (°F)	375	230
Total Particulate Emissions*		
Concentration (g/dscm)	0.57	1.15
Rate (lb/hr)	0.09	0.14
Factor (g/kg wood, Dry)	14	30
($g/10^4$ Btu, Net)	10	24
Front-half (% of total)	25	19
Creosote (mg/m^2 kg)	88	317
Hydrocarbons (ppm)	46	63
Hydrocarbons (g/kg wood, Dry)	3.9	5.8
Carbon monoxide (g/kg wood, Dry)	80	150
Opacity (observer, %)	<5	13
Stack Gas Composition		
CO_2 (%)	4.0	3.3
CO (%)	0.3	0.5
O_2 (%)	16.4	17.5
N_2 (%)	79.3	78.7
Moisture (%)	6.5	--
Excess Air (%)	347	498
Stack Gas Flow (dscf/hr)	2500	1960
Efficiency, (net, %)**	68	64

---

* Oregon DEQ Method 7 (EPA Method 5 with back-half)

** Since techniques for determining appliance efficiency vary tremendously, the reported efficiency results should be used only as relative values for comparison between stoves and test runs under the specific operating conditions of this program.

TABLE 27

Results -- Catalytic Modified Combustion Stove
(By Test Phase)

PARAMETERS	RUN NUMBER	
	17/1	17/2
Fuel Charge (lb, Wet)	18.7	
(lb, Dry)	15.0	
Fuel Moisture (%, Wet)	20	
(%, Dry)	25	
Sample Time (Minutes)	50	125
Fuel Burned (lb, Wet)	8.2	9.1
(lb, Dry)	6.5	7.3
Burn Rate (lb/hr, Wet)	9.8	4.4
(lb/hr, Dry)	7.8	3.5
Temperatures		
Combustion (°F)	568	459
Surface (°F)	325	232
Stack (°F)	237	224
Total Particulate Emissions*		
Concentration (g/dscm)	1.59	0.90
Rate (lb/hr)	0.25	0.10
Factor (g/kg wood, Dry)	32	28
($g/10^4$ Btu, Net)	--	--
Front-half (% of total)	19.0	19.3
Creosote (mg/m^2 kg)	--	--
Hydrocarbons (ppm)	78.5	55.8
Hydrocarbons (g/kg wood, Dry)	5.6	6.2
Carbon monoxide (g/kg wood, Dry)	160	150
Opacity (observer, %)	19	10
Stack Gas Composition		
CO_2 (%)	4.3	2.8
CO (%)	0.7	0.4
O_2 (%)	16.5	17.9
N_2 (%)	78.5	78.9
Moisture (%)	10.0	4.6
Excess Air (%)	354	578
Stack Gas Flow (dscf/hr)	2500	1750
Efficiency, (net, %)	--	--

---

* Oregon DEQ Method 7 (EPA Method 5 with back-half)

TABLE 28
Bacharach Smoke Spot Results

RUN	SAMPLE TIME	SPOT DENSITY	
		Sample Location	
		Sampling	Outlet
16 1015-1215	1029 - 1031	5	5
	1114 - 1118	5	5
	1210	5	-
	Ave. Temperature	320°F	233°F
17 1416-1711	1445 - 1448	6	6
	1540 - 1544	6	5
	1634 - 1637	6	6
	Ave. Temperature	251°F	157°F

TABLE 29

Visible Emissions Observation Log

RUN	RUN TIME		VISIBLE EMISSIONS MEASUREMENT				
	Clock · Phase 1 · Phase 2	Elasped Min. · Phase 1 · Phase 2	Time Period	Minutes Observed	Opacity (Percent)	Opacity Range (Percent)	Average Opacity (Percent) Phases 1,2,total
16	1015 - 1215	120	1019 - 1029	10	<5	<5 - 10	<5
			1200 - 1209	10	<5	0 - <5	
17	1416 - 1506	50	1418 - 1427	10	19	15 - 25	19
	1506 - 1711	125	1540 - 1549	10	11	10 - 15	11
		175	1659 - 1708	10	10	10 - 15	13

TABLE 30

CATALYST TEMPERATURES

RUN 16

TIME Clock	Elapsed		TEMPERATURE, °F precatalyst Tertiary Air	 Combustion Chamber	 post-catalyst
1015	1.5		547	730	1046
	4.5		911	840	1121
	10		644	686	782
	20		568	642	726
	30		522	604	632
	40		447	582	579
	50		450	647	697
1115	60		447	610	646
	70		421	599	629
	85		397	607	604
	95		665	670	598
	105		408	669	624
	110		---	688	602
1215	120		---	597	559
		Average Value	535	655	703

Average ΔT across catalyst is 50°F.

TABLE 30 (Cont.)

CATALYST TEMPERATURES

RUN 17

TIME		TEMPERATURE, °F		
		precatalyst		post-catalyst
Clock	Elapsed	Tertiary Air	Combustion Chamber	
1416	0	470	---	804
	13	472	583	550
	20	442	556	560
	30	451	611	530
	40	414	550	499
	50	387	520	479
	60	---	507	457
	70	365	502	446
	80	345	476	458
	90	---	416	396
	100	295	396	395
	110	279	388	373
	120	261	375	358
	130	---	461	468
	140	358	556	525
	150	---	517	489
	160	323	457	406
	175	---	423	370
	Average Value	374	488	476

Average ΔT across catalyst is 0°F.

FIGURE 55

Run 16

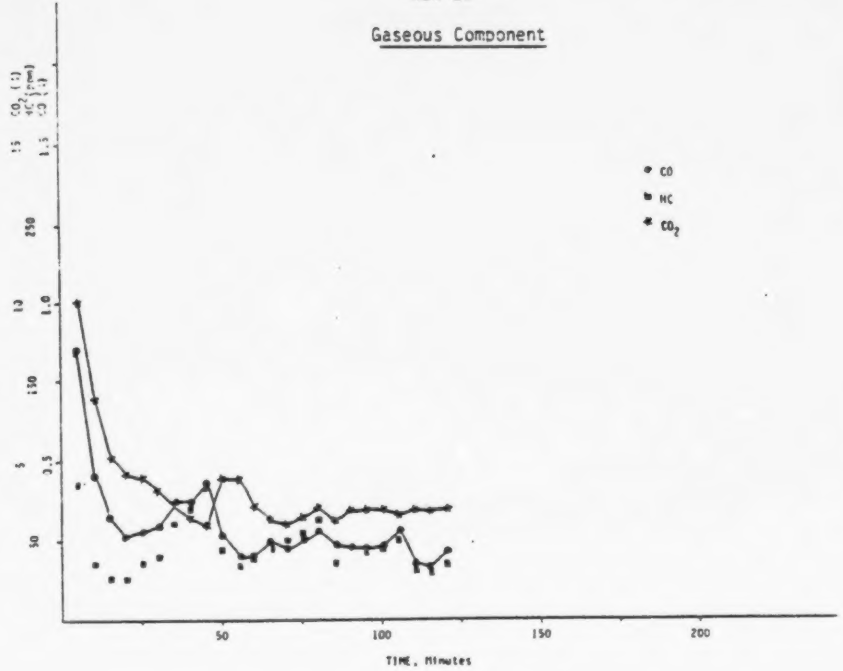

Gaseous Component

FIGURE 56

Run 16

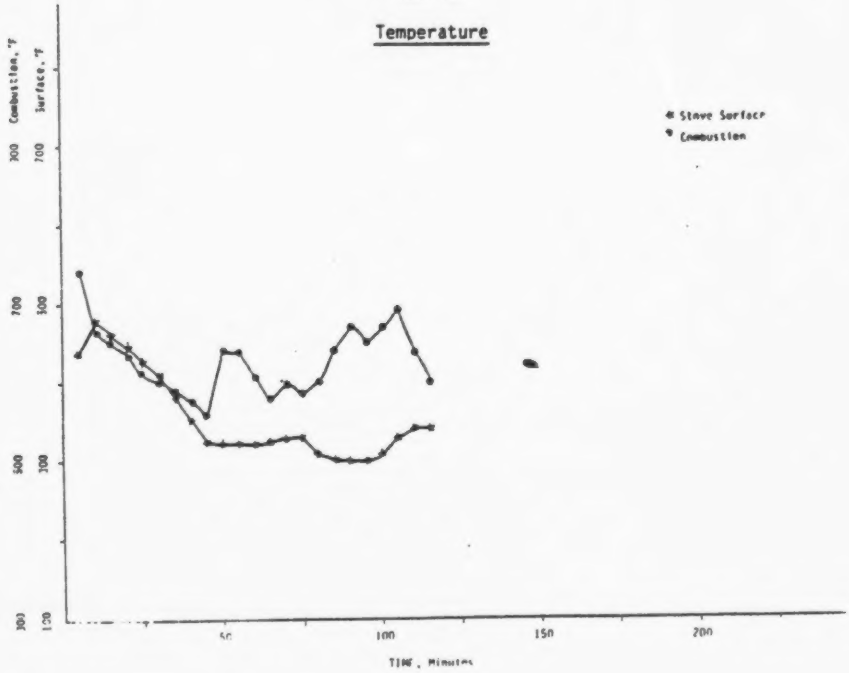

Temperature

FIGURE 57

Run 17

Gaseous Component

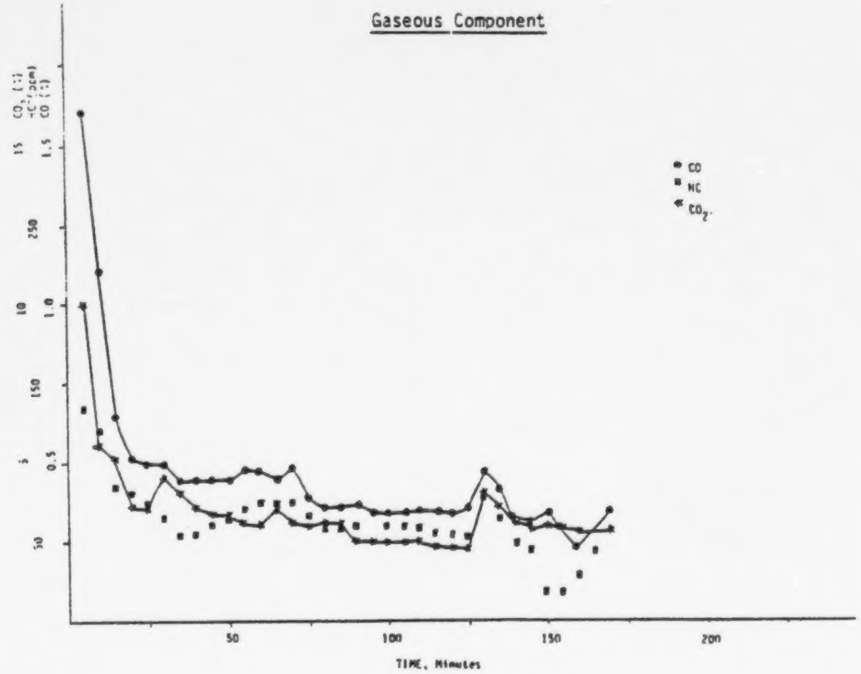


FIGURE 58

Run 17

Temperature

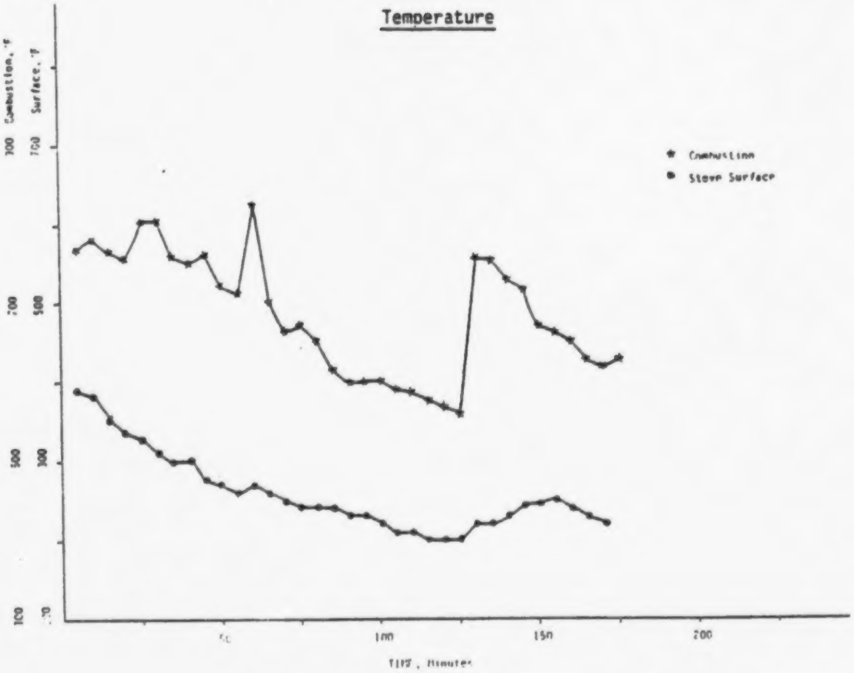


FIGURE 59

Opacity and Smoke Spot Density
vs
Time
(Run 16)

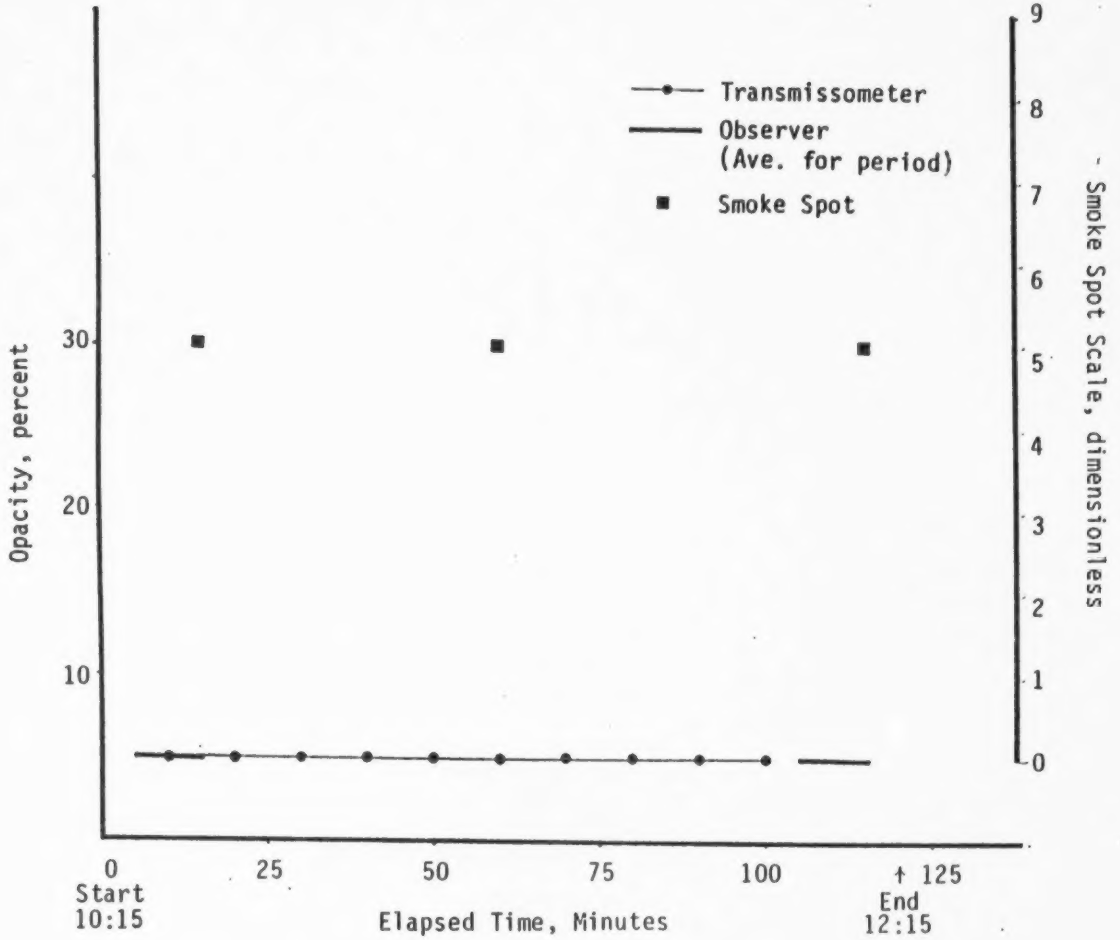


FIGURE 60

Opacity and Smoke Spot Density
vs
Time
(Run 17)

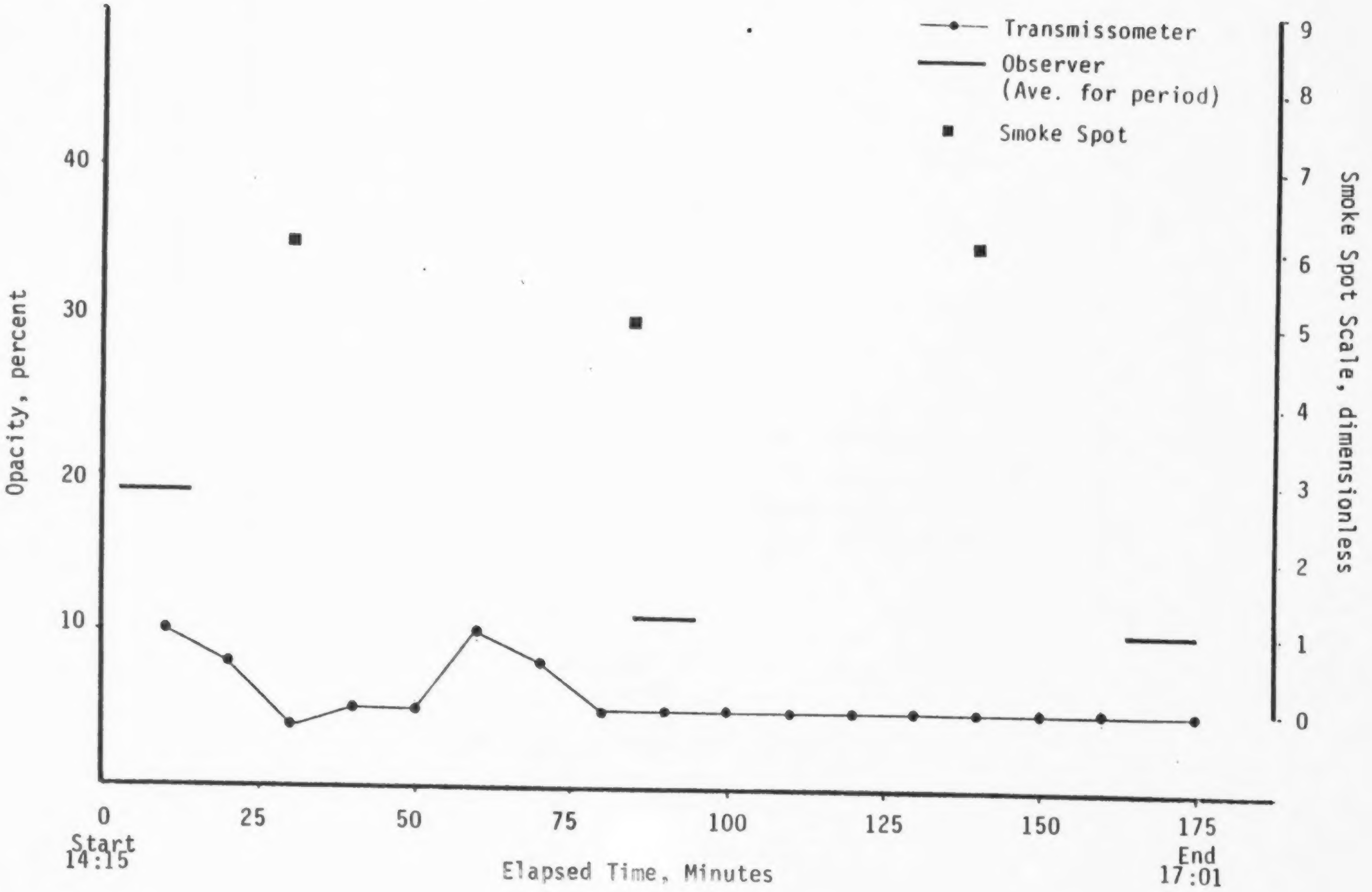


TABLE 31

OPERATION LOG

RUN 16

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1015	17.6			Begin Run, damper full open; 3rd level air full open.
1020	14.4	740	440	Closed damper to 3/8" open at 1021.
1026				Closed damper to 1/4" open.
1035				Damper automatically opened to 1/2".
1214	1.2	597	340	End of Burn.

TABLE 31 (Cont.)

RUN 17

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1416	18.7			Begin Run; damper full open; 3rd level air full open.
1421	17.0	569	390	Closed damper to 1/4" at 1418.
1427				Closed damper to 3/8" open.
1506	10.5	520	275	End of Phase I.
1514				Open damper to 3/4".
1552				Open damper to 1".
1616	4.7	375	200	Open damper at 1612.
1625				Rearrange wood to single pile.
1633				Closed damper to 1".
1650				Open damper to full open.
1711	1.4	423	220	End of Burn.

CERAMIC STOVE

Due to the design of this stove, the fuel burn rate during Runs 18 and 19 were significantly higher than the burn rate called for in the test protocol; 6.5 and 3.9 kg/hr, respectively. This high burn rate characterized by a high combustion chamber temperature (1200 - 1500° F), is no doubt a factor in the low emissions rate measured during these runs. The fact that this stove does operate at such a high burn rate makes it difficult to compare the emissions results to the results of the other stoves tested at much lower burn rates. Excess air for these two tests averaged 80 percent. The average length of the burn was only 80 minutes, due to the high burn rate.

Several testing anomalies occurred during these runs. First, no Bacharach smoke spot tests were conducted. Secondly, although visual emission readings were taken for these runs, the observer was not Method 9 certified. This is not expected to have any impact on the results since no visible emissions were noted during the test runs; consequently, no judgement of opacity was required. Finally, at the beginning of Phase 2 for Run 19, the thermocouple monitoring the stack temperature malfunctioned. The obviously erroneous temperature readings taken prior to fixing the thermocouple were deleted from the test calculations.

Note the impact on CO/CO_2 emissions and combustion chamber temperature in Run 19 when the fire was stoked (045 elapsed time).

TABLE 32

Results -- Ceramic Stove

PARAMETERS	RUN NUMBER	
	18	19
Fuel Charge (lb, Wet)	19.1	19.5
(lb, Dry)	16.0	15.6
Fuel Moisture (%, Wet)	17.4	20
(%, Dry)	21	25
Sample Time (Minutes)	61	99
Fuel Burned (lb, Wet)	17.8	18.0
(lb, Dry)	14.4	14.4
Burn Rate (lb/hr, Wet)	17.5	10.9
(lb/hr, Dry)	14.2	8.7
Temperatures		
Combustion (°F)	1519	1195
Surface (°F)	--	207
Stack (°F)	779	604
Total Particulate Emissions*		
Concentration (g/dscm)	0.16	0.13
Rate (lb/hr)	0.02	0.01
Factor (g/kg wood, Dry)	1	2
(g/10^4 Btu, Net)	0.7	1.5
Front-half (% of total)	63.1	48.6
Creosote (mg/m^2 kg)	56	27
Hydrocarbons (ppm)	15	15
Hydrocarbons (g/kg wood, Dry)	0.4	0.6
Carbon monoxide (g/kg wood, Dry)	20	50
Opacity (observer, %)	-0-	-0-
Stack Gas Composition		
CO_2 (%)	12.6	8.1
CO (%)	0.2	0.4
O_2 (%)	8.2	10.7
N_2 (%)	79.0	80.9
Moisture (%)	15.0	--
Excess Air (%)	63	97
Stack Gas Flow (dscf/hr)	1850	1720
Efficiency, (net, %)**	68	65

---

* Oregon DEQ Method 7 (EPA Method 5 with back-half)

** Since techniques for determining appliance efficiency vary tremendously, the reported efficiency results should be used only as relative values for comparison between stoves and test runs under the specific operating conditions of this program.

TABLE 33

Results -- Ceramic Stove
(By Test Phase)

PARAMETERS	RUN NUMBER 19/1	RUN NUMBER 19/2
Fuel Charge (lb, Wet)	19.5	
(lb, Dry)	15.6	
Fuel Moisture (%, Wet)	20	
(%, Dry)	25	
Sample Time (Minutes)	25	74
Fuel Burned (lb, Wet)	8.3	9.7
(lb, Dry)	6.6	7.8
Burn Rate (lb/hr, Wet)	19.9	7.9
(lb/hr, Dry)	15.8	6.3
Temperatures		
Combustion (°F)	1260	1171
Surface (°F)	200	209
Stack (°F)	634	485
Total Particulate Emissions*		
Concentration (g/dscm)	0.36	0.12
Rate (lb/hr)	0.05	0.01
Factor (g/kg wood, Dry)	1.5	1.6
($g/10^4$ Btu, Net)	--	--
Front-half (% of total)	53.6	42.9
Creosote (mg/m^2 kg)	51	8
Hydrocarbons (ppm)	26	11
Hydrocarbons (g/kg wood, Dry)	0.9	0.5
Carbon monoxide (g/kg wood, Dry)	70	50
Opacity (observer, %)	-0-	-0-
Stack Gas Composition		
CO_2 (%)	10.4	7.3
CO (%)	0.6	0.3
O_2 (%)	10.5	10.8
N_2 (%)	78.5	81.7
Moisture (%)	17.1	7.4
Excess Air (%)	96.7	97.2
Stack Gas Flow (dscf/hr)	2400	1390
Efficiency, (net, %)	--	--

---

* Oregon DEQ Method 7 (EPA Method 5 with back-half)

TABLE 34

Bacharach Smoke Spot Results

RUN	SAMPLE TIME	SPOT DENSITY	
		Sample Location	
		Sampling	Outlet
18	No Data	---	---
19	No Data	---	---

TABLE 35

Visible Emissions Observation Log

RUN	RUN TIME		VISIBLE EMISSIONS MEASUREMENT				
	Clock • Phase 1 • Phase 2	Elasped Min. • Phase 1 • Phase 2	Time Period	Minutes Observed	Opacity (Percent)	Opacity Range (Percent)	Average Opacity (Percent) Phases 1,2,total
18	1044 - 1145	61	1032 - 1041	10	-0-	-0-	-0-
			1132 - 1141	10	-0-	-0-	
			1142 - 1151	10	-0-	-0-	
19	1405 - 1544	99					-0-

FIGURE 61

Run 18

Gaseous Component

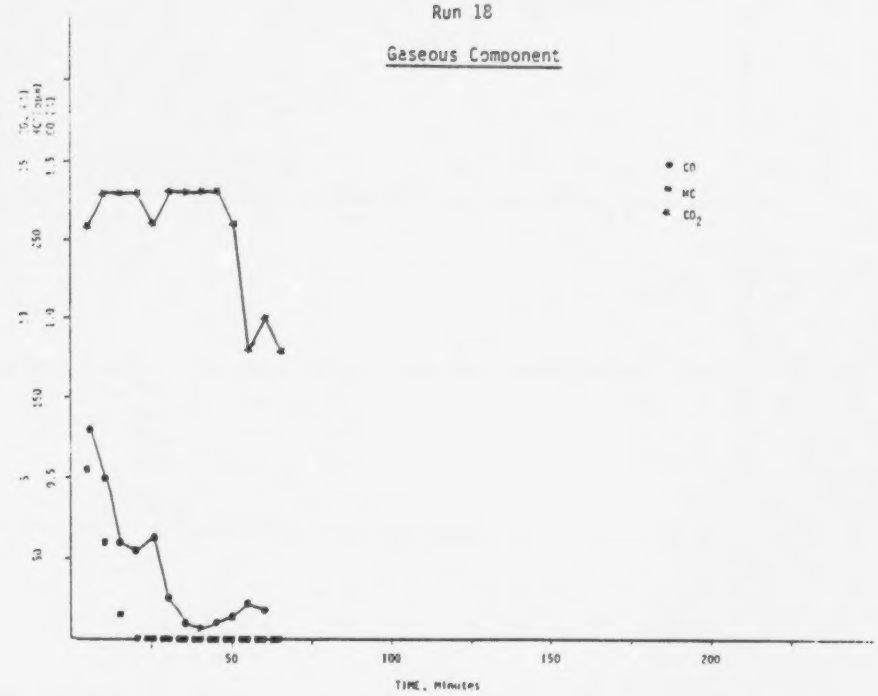


FIGURE 62

Run 18

Temperature

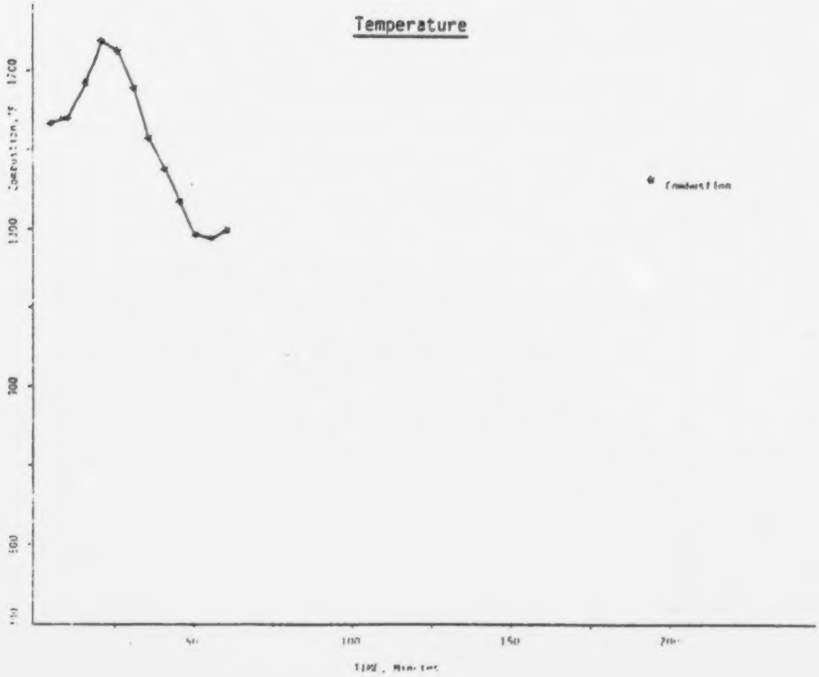


FIGURE 63

Run 19

Gaseous Component

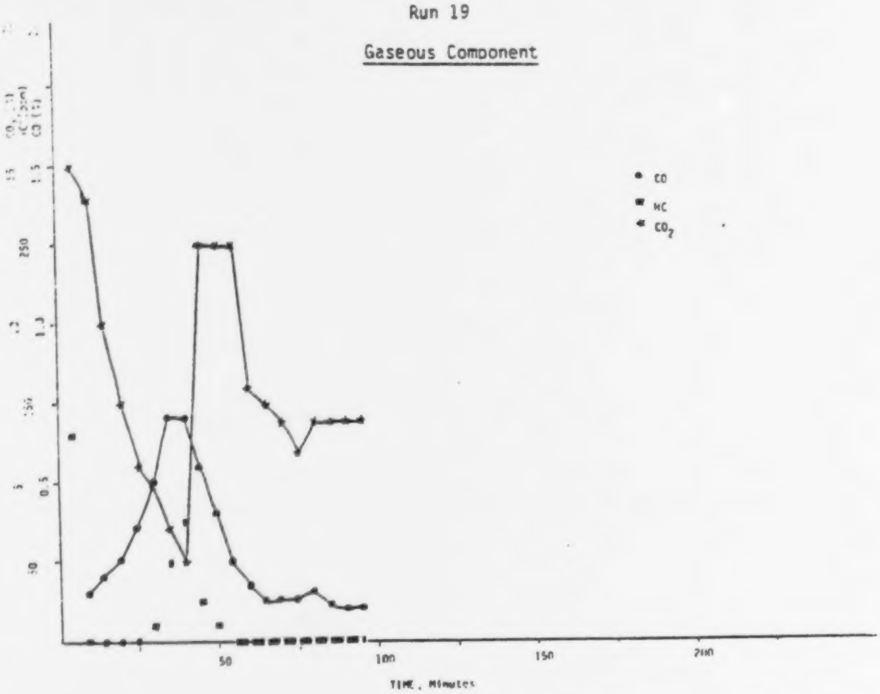


FIGURE 64

Run 19

Temperature

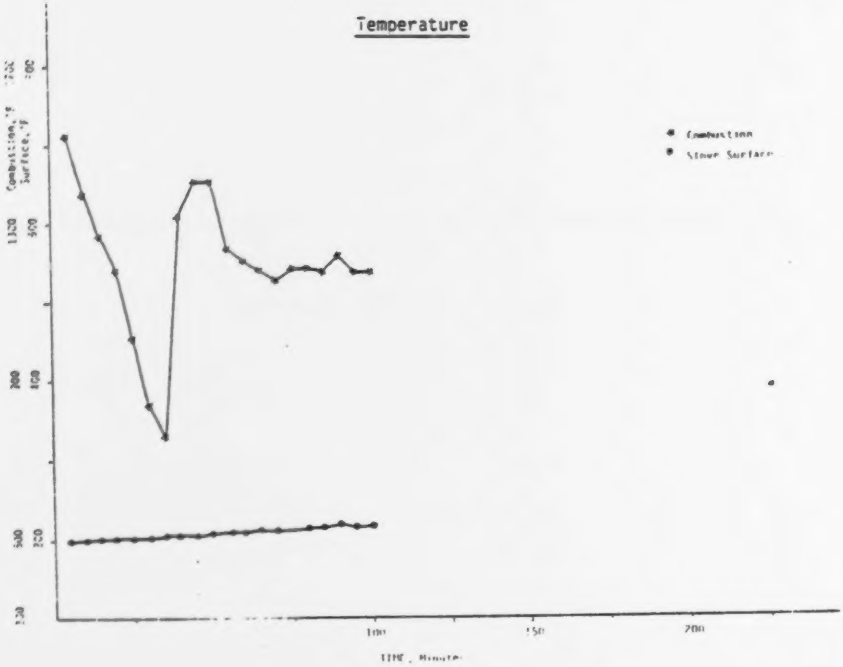


FIGURE 65

Opacity and Smoke Spot Density
vs
Time
(Run 18)

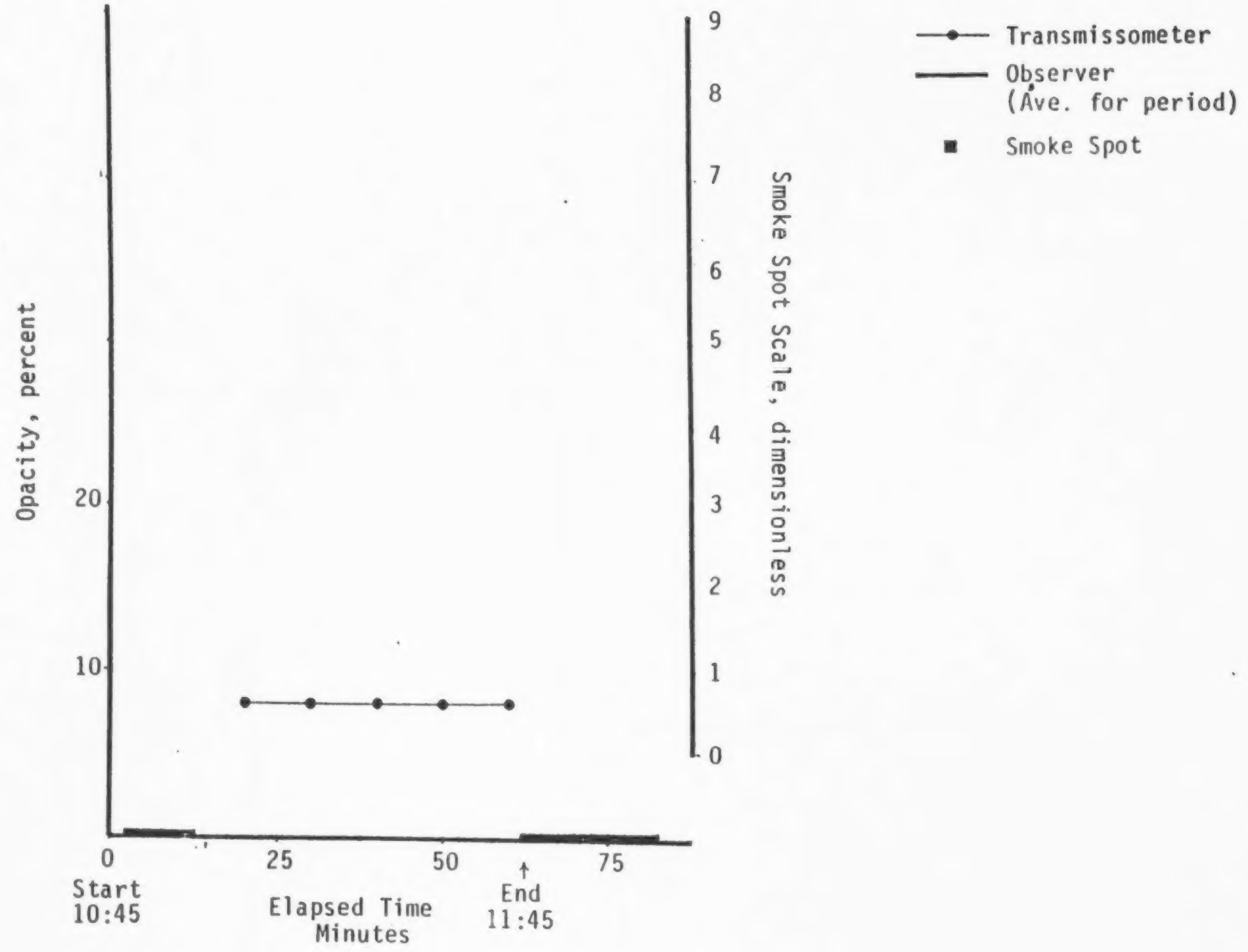


FIGURE 66

Opacity and Smoke Spot Density
vs
Time
(Run 19)

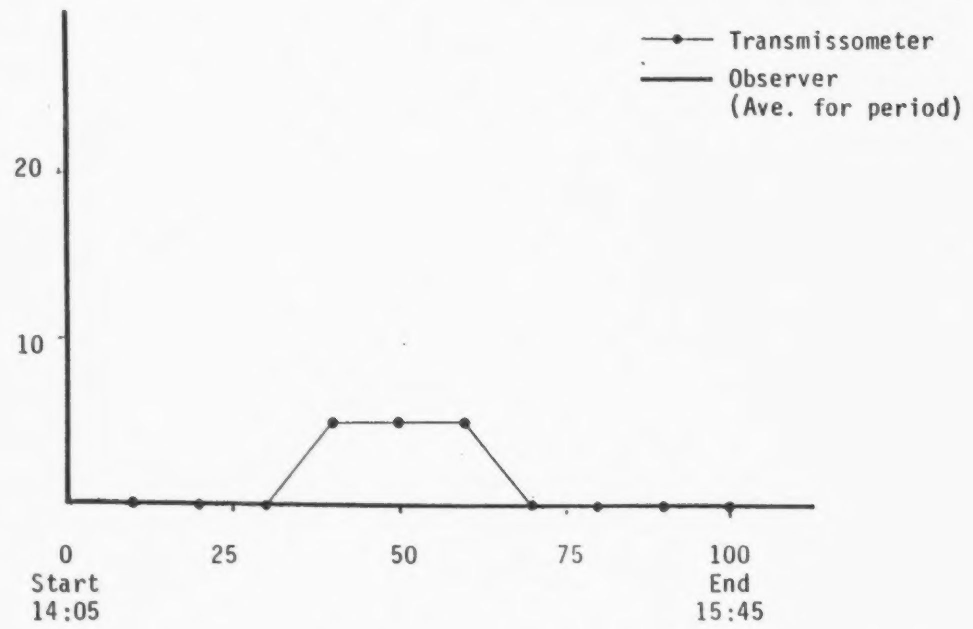


TABLE 36

OPERATION LOG

RUN 18

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1044	19.1			Begin Run; stack damper full open; door ajar.
1045				Latch door.
1047				Fully close damper
1055				Stove surface warm to touch.
1144	1.3	1297	---	End of Burn.

TABLE 36 (Cont.)

RUN 19

TIME	FUEL WT. (lb)	COMBUSTION TEMPERATURE (°F)	STOVE SURFACE TEMPERATURE (°F)	COMMENTS
1405	19.5		196	Begin Run.
1407				Close stack damper.
1430				End Phase I.
1444				Rearrange logs.
1544	1.5	1170	220	End of Burn.

RESIDENTIAL WOOD COMBUSTION STUDY

TASK 5

EMISSIONS TESTING OF WOOD STOVES

Volume 2 of 4

THIS REPORT CONSISTS OF SEVERAL DIFFERENT PARTS.

THEY ARE LISTED BELOW FOR YOUR CONVENIENCE.

EPA 910/9-82-089a	Residential Wood Combustion Study Task 1 - Ambient Air Quality Impact Analysis
EPA 910/9-82-089b	Task 1 - Appendices
EPA 910/9-82-089c	Task 2A - Current & Projected Air Quality Impacts
EPA 910/9-82-089d	Task 2B - Household Information Survey
EPA 910/9-82-089e	Task 3 - Wood Fuel Use Projection
EPA 910/9-82-089f	Task 4 - Technical Analysis of Wood Stoves
EPA 910/9-82-089g	Task 5 - Emissions Testing of Wood Stoves Volumes 1 & 2
EPA 910/9-82-089h	Task 5 - Emissions Testing of Wood Stoves Volumes 3 & 4 (Appendices)
EPA 910/9-82-089i	Task 6 - Control Strategy Analysis
EPA 910/9-82-089j	Task 7 - Indoor Air Quality

DISCLAIMER

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DISCUSSION OF RESULTS

GENERAL

In this section, the emission test results are discussed and evaluated with respect to the objectives of the study. The results of the moisture tests, simplified test procedures, and appliance performance are evaluated.

The tests were conducted at an average burn rate of 2.5 kg/hour. During the tests the stove surface temperatures averaged in the 350 - 400°F range, the combustion chamber temperature averaged 500 - 600°F, and the stack temperature averaged 250 - 300°F.

The average total emission rate for these tests (excluding fuel moisture and cold start emissions) was 19 g/kg. Front-half emissions averaged 21% of the total. Carbon monoxide and hydrocarbon emissions averaged 115 and 8.7 g/kg, respectively. Creosote deposition averaged 330 mg/m^2 kg. Average opacities measured by the visible emission observer and transmissometer were 21 and 18 percent, respectively.

Numerous figures correlating various emission factors are presented in this section. Several notations are included with the data points plotted on these figures and have the following meanings, unless otherwise noted:

L	Low moisture fuel test
LC	Low moisture fuel test, cold start
H	High moisture fuel test
HC	High moisture fuel test, cold start
MC	Medium moisture fuel test, cold start
"Star"	Not included in correlation

COMPARISON OF PARTICULATE RESULTS AMONG APPLIANCES

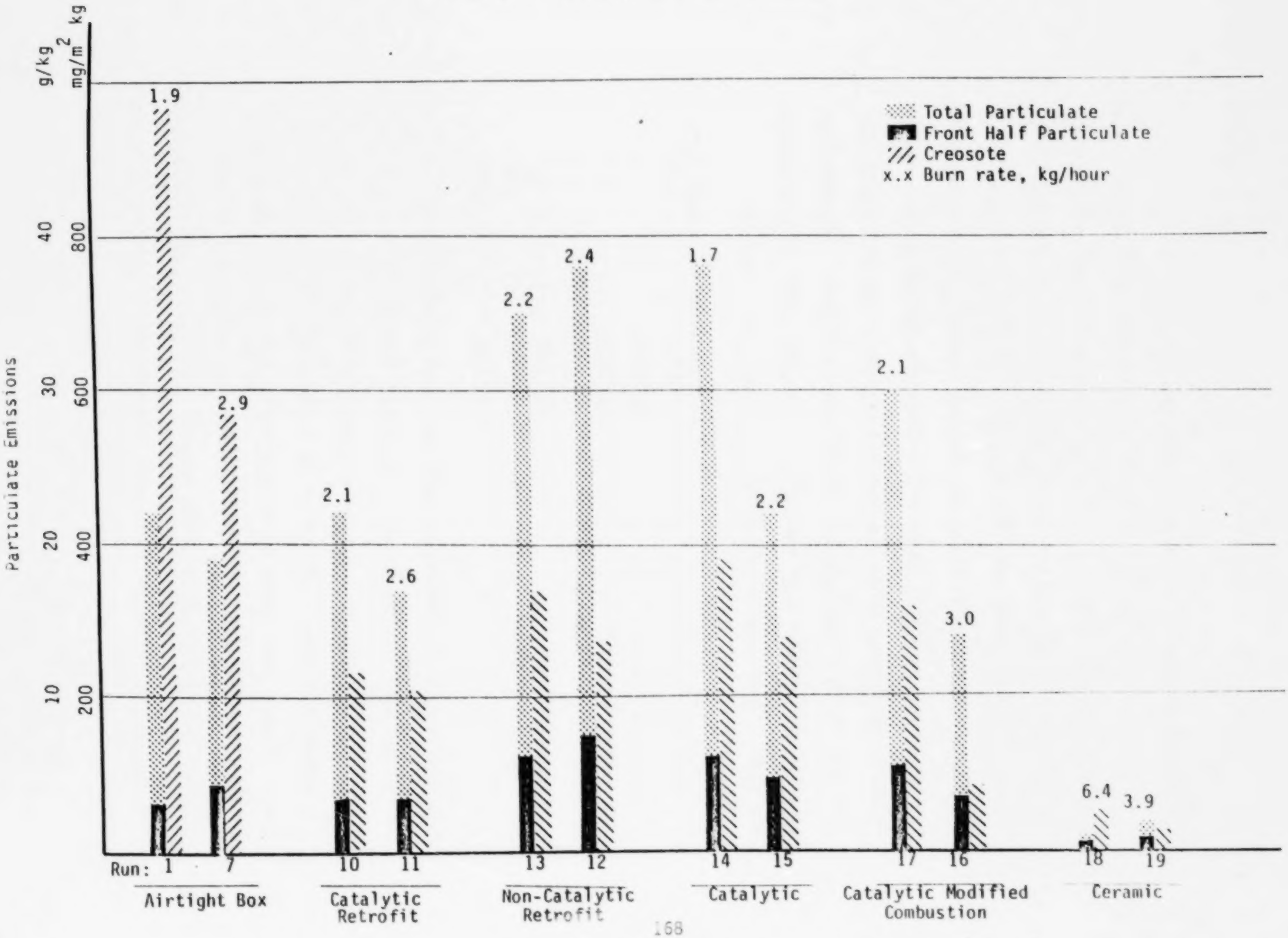
Figure 67 graphically presents the particulate emission test results. The test runs conducted for fuel moisture evaluation and evaluation of cold start emissions are not included in the graph. Examination of the results indicates that, with the exception of the ceramic stove, no significant reduction in emissions occurred with the improved technology stoves for the operating conditions under which the stoves were tested. Although the ceramic stove did have significantly less emissions, the burn rate for this appliance was significantlly higher. The dependency of emissions level on burn rate will be discussed later in this section. The average emissions for the different stoves are as follows:

	Total, Front-half g/kg	Burn Rate kg/hr
Airtight Box	21 (5.3)	2.4
Catalytic Retrofit	20 (3.5)	2.4
Non-Catalytic Retrofit	37 (6.8)	2.3
Catalytic Box	31 (5.4)	2.0
Catalytic Modified Combustion	22 (4.6)	2.5
Ceramic	1.5 (0.8)	5.2

Note that even with assuming an equivalent heat output (Btu/hr), although the ceramic stove would consume twice as much fuel as the other appliances in the same time period, the emissions would be 85% less (8 g/hr vs approximately 48 g/kg). Of course, it is reasonable to expect that at double the burn rate, there would be a higher heat output. The problem is that it is not really possible to determine what percent of emissions reduction can be attributed to the ceramic stove per se, and what percent is simply due to the higher burn rate. Nonetheless, it must be noted that

FIGURE 67

Summary of Particulate Emission Results



the high burn rate is a characteristic of this stove; consequently, one would expect it to operate with this low emission level under normal operating conditions.

Note that neither the catalytic or non-catalytic retrofit reduced emissions at the conditions under which tests were run. The duplicate test runs (for each appliance) were conducted at close to the same conditions and the emission results compared well for the paired samples. The non-catalytic retrofit actually yielded higher results than the airtight box stove; there is no explanation for this result. The tests with the catalytic add-on device yielded results nearly identical to the airtight stove alone.

The measured creosote deposition followed the same trend as the particulate emissions with one major exception. The measured creosote emissions for the airtight box stove (Runs 1 and 7) were significantly higher than for the other test runs of similar emission rate. The creosote results particularly in relation to measured emission rates, are discussed in more detail in a later section of this report.

The second major point which should be noted from the results relates to the significant variation in emissions between the paired runs for both the catalytic and catalytic modified combustion stoves. These data warrant further discussion because they illustrate the large impact operating conditions can have on appliance emissions. Table 37 summarizes the operating conditions for the two stoves during the four test runs. Note that in both cases an approximate 40% increase in burn rate results in a 40 - 50% decrease in emissions.

TABLE 37

Comparison of Operating Parameter and Emissions:
Airtight Box, Catalytic, and
Catalytic Modified Combustion Appliances

STOVE	RUN	BURN RATE	TEMPERATURE (AVERAGE ° F)					EMISSIONS	
			Combustion	Surface	Post Catalyst (ave)	(max)	Catalyst ΔT	Part. g/kg	CO g/kg
Airtight	1	1.9	510	340	-	-	-	22	190
	7	2.9	610	510	-	-	-	19	160
Catalytic	14	1.7	600	390	800	1130	200	38	120
	15	2.2	820	412	850	1100	100	23	50
Catalytic Modified Combustion	17	2.1	490	260	480	800	-0-	30	150
	16	3.0	630	350	700	1120	50	14	80

Particularly for the catalytic modified combustion appliance it is clearly seen that the slight change in operating conditions as measured by the combustion and surface temperatures results in this significant decrease in particulate emissions. This same trend occurred for carbon monoxide emissions (see Table 37). Note that for Run 17, the stove was clearly operating at a temperature (490° F) insufficient for proper catalyst operation (manufacturer indicates minimum temperature of 600°F required at point measured). The importance of operating conditions cannot be overstressed.

Figure 68 graphically presents a correlation between burn rate and particulate emissions. The correlation does not include the data obtained during the cold start or fuel moisture tests, although these data points are indicated in the figure. The correlation indicates a strong exponential increase in emissions for a decreasing burn rate. This type relationship is similar to that previously reported in the literature[1d], although this correlation indicates a greater impact than previously reported. The relationship determined from 13 test runs conducted for the Oregon DEQ[1d] also is plotted on this figure, for comparison.

Figures 69 and 70 graphically present the relationship between burn rate and emissions in a different manner. Figure 69 is for total particulate emissions and Figure 70 for front-half emissions only. An additional factor, the mass of fuel charged, is taken into account in these correlations. This type correlation is extremely useful because it essentially allows one to indirectly normalize the burn rate

FIGURE 68

Total Particulate Emissions
vs
Burn Rate

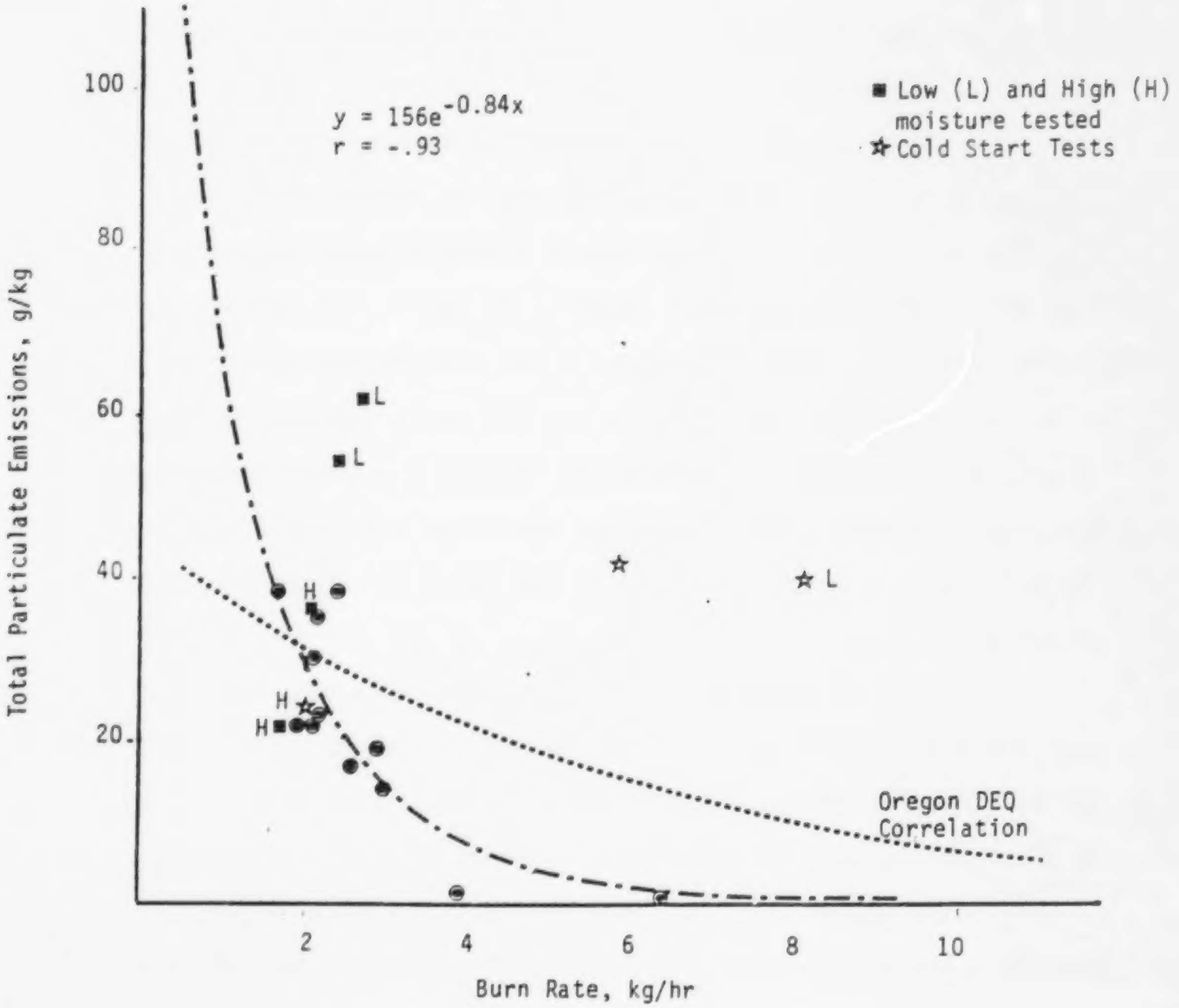


FIGURE 69

Total Particulate Emissions
vs
Fuel Load/Average Combustion Rate

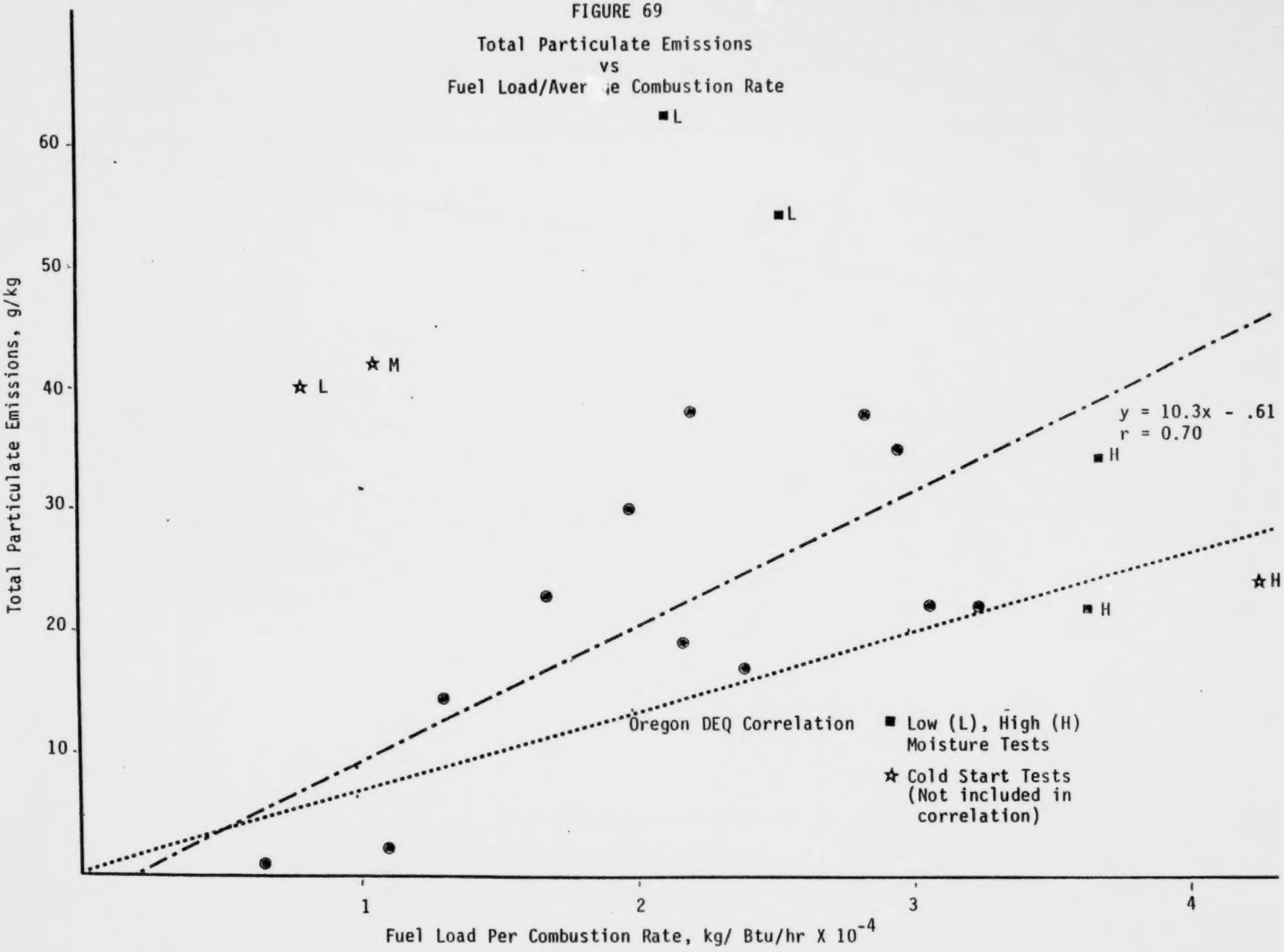
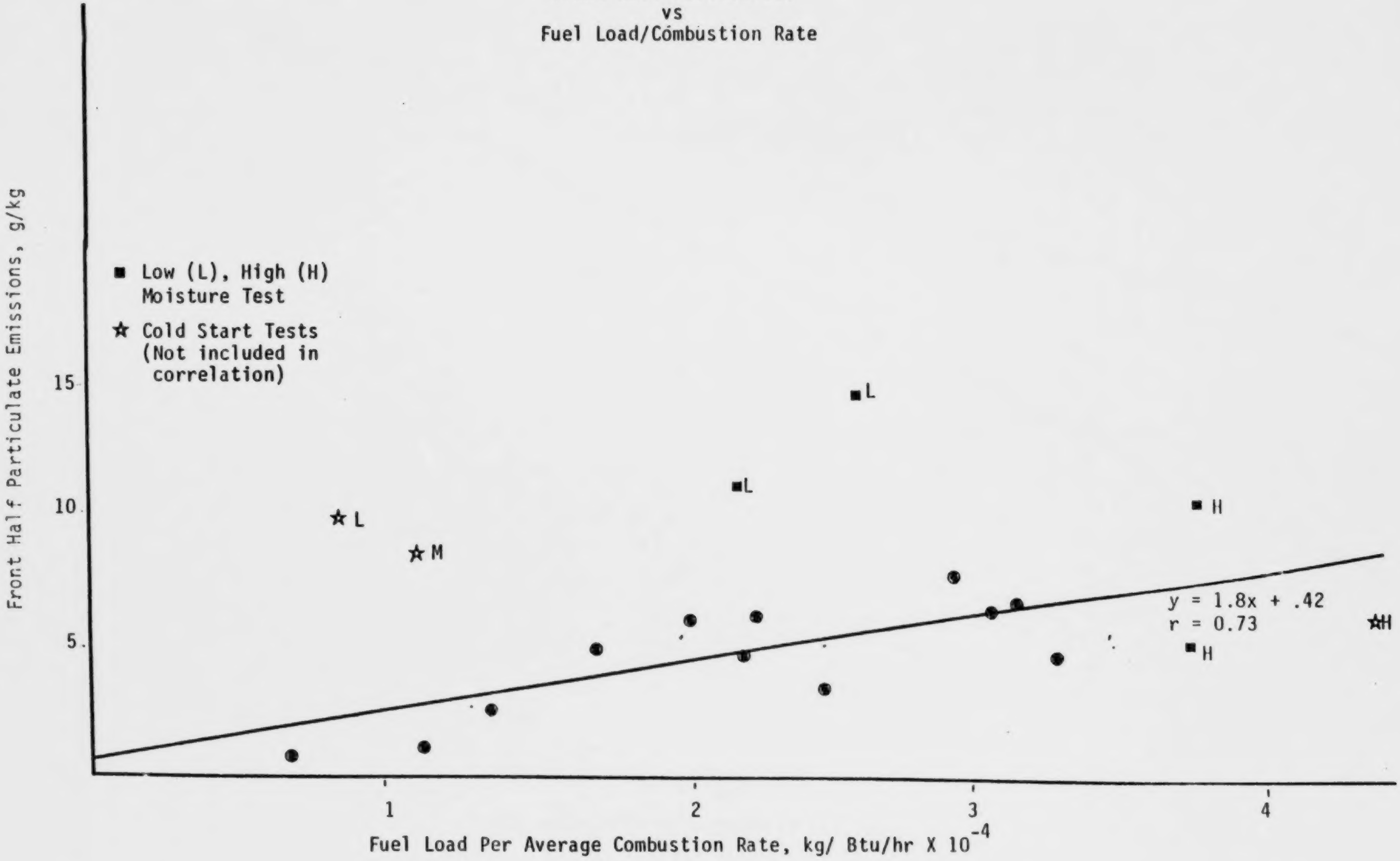


FIGURE 70

Front Half Particulate
vs
Fuel Load/Combustion Rate



for stove size. For example, it is not necessarily reasonable to compare a stove with a 6 ft^3 volume and a stove with a 3 ft^3 volume at the same burn rate (2.0 kg/hr); since the larger stove holds twice as much fuel, it is reasonable to expect this stove to be rated for a higher heat output rate and therefore, to be operated at a higher burn rate; 4.0 kg/hr, for example. Given a combustion rate of 4.0 kg/hr for the larger stove and assuming twice the fuel load for twice the volume, then the "fuel load per combustion rate" factor (M/Q) for the two stoves would be equivalent. This assumes that some constant factor for fuel load to stove volume (M/V) also is used. Table 38 presents a summary of the fuel load combustion data.

The relationship presented here and in Figure 68 (emissions increasing exponentially with burn rate) are somewhat contradictory. If one assumes a constant fuel load then the correlation in Figures 69 and 70 would indicate a linear increase in emissions with burn rate. The correlation factor for the exponential relationship is significantly better (.93 vs .70). Nonetheless, it seems logical that when characterizing stove operation, both the fuel load and burn rate must be taken into account. Consequently, the fuel/load combustion rate correlation is really of more practial use. This parameter used in conjunction with a constant fuel mass/stove volume ratio could be used to help establish desired stove operating parameters (i.e., burn rate) for tests conducted to compare emissions results.

The correlation obtained during Oregon DEQ's tests of thirteen stoves is shown in Figure 69 for comparison. The DEQ tests were conducted in the same basic fuel load/combustion rate range (1.5 - 3.5 kg/Btu/hr x 10^{-4}). For this test series, emission levels slightly higher than those obtained by DEQ were measured at the corresponding fuel load/combustion rate.

TABLE 38

Fuel Load and Combustion Rate Summary

RUN	FUEL LOAD (Wet) M	HEAT RELEASE RATIO Q	FUEL COMBUSTION RATIO M/Q	STOVE VOLUME V	FUEL VOLUME RATIO M/V	FUEL LOAD (Dry) M'	FUEL COMBUSTION RATE RATIO(Dry) M'/Q	FUEL VOLUME (Dry) M'/V
	kg	10^4 Btu/hr		m^3	kg/m^3	kg		
1	11.9	3.8	3.1	0.17	70	9.4	2.5	55
7	12.9	5.8	2.2	0.17	76	10.3	1.8	61
10	14.0	4.2	3.3	0.17	82	11.4	2.7	67
11	12.6	5.2	2.5	0.17	74	10.2	2.0	60
12	14.0	4.8	2.9	0.17	82	11.3	2.4	66
13	13.3	4.4	3.0	0.17	76	10.8	2.5	64
14	7.6	3.4	2.3	0.07	108	6.3	1.9	90
15	7.5	4.4	1.7	0.07	107	6.0	1.4	86
16	8.0	6.0	1.3	0.08	100	6.5	1.1	81
17	8.5	4.2	2.0	0.08	106	6.8	1.6	85
18	8.7	12.7	0.7	0.09	97	7.3	0.6	81
19	8.9	7.8	1.1	0.09	99	7.1	0.9	79
2	12.5	4.8	2.6		74	11.0	2.3	
3	15.7	4.2	3.8		92	6.9	1.6	
5	11.8	5.4	2.2		69	10.4	1.9	
9	12.5	3.4	3.7		74	5.5	1.6	
4	13.5	16.1	0.8		79	11.9	0.7	
6	12.4	11.5	1.1		73	10.0	0.9	
8	17.3	4.0	4.4		102	7.7	1.9	

STOVE EFFICIENCY

Stove efficiencies (net useable heat output) did not vary significantly from test run to test run with the exception of the high fuel moisture tests. Table 39 summarizes the results. The average stove efficiency was 66 percent. For the high moisture fuel tests the efficiency dropped significantly to 45 percent, primarily due to the additional heat loss from the latent heat content of the water.

The ceramic stove efficiency was determined to be 67 percent, even though stack gas temperatures for this stove were particularly high (650°F), resultin in excessive stack losses. However, the high combustion efficiency of this stove compensated for the large stack losses; a heat exchange system on the stack of this unit could increase the net efficiency.

Since techniques for determining appliance efficiencies vary tremendously, it is recommended that the results reported here be used solely for comparing results among the stoves tested in this program.

TABLE 39

Results:
Stove Efficiency

STOVE	RUN	NET EFFICIENCY (%)*
Airtight Box	1	65
	7	66
	AVE	65
Airtight Box (Low Moisture Fuel)	2	60
	5	62
	AVE	61
Airtight Box (High Moisture Fuel)	3	43
	9	48
	AVE	45
Airtight Box (Non-Catalytic Retrofit)	10	68
	11	71
	AVE	69
Airtight Box (Catalytic Retrofit)	12	60
	13	66
	AVE	63
Catalytic Box	14	68
	15	71
	AVE	69
Catalytic Modified Combustion	16	68
	17	64
	AVE	66
Ceramic	18	68
	19	65
	AVE	66

* Since techniques for determining appliance efficiencies vary tremendously, the reported efficiency results should be used only as relative values for comparison between stoves tested under the specific operating conditions of this program.

PARTICULATE EMISSIONS -- FIRST PHASE TESTS

As previously mentioned for some of the test runs, a separate particulate sample was taken during the first part (phase) of the test burn. A total of 11 first phase samples were taken with 3 of these samples being taken from a test burn started from a cold stove condition (i.e., no hot coal bed). Figure 71 graphically presents the first phase test results; the results are summarized in Table 40. One reason for taking the first phase samples was to determine if the emissions from this phase of the test burn were significantly higher than during the rest of the burn. From Table 40 (last column) it is seen that in terms of g/kg, total particulate emissions for Phase 1 were generally the same or higher than emissions from Phase 2 (Run 1 is the exception). Similarly, the measured concentration for Phase 1 was more often higher than the Phase 2 concentration. However, the data can be examined in a different manner; columns 2 and 4 list the percent of the total fuel consumed and total mass emitted during the first phase of the test. Examination of these data indicate that in general, the percentages compare favorably. In other words, the percent of the total emissions during Phase 1 with the percent of fuel consumed is consistent. For example, in Run 10, 37 percent of the fuel was consumed during the first phase and 39 percent of the total mass emitted was emitted during the first phase. Nonetheless, on an absolute basis a significant portion of the total mass emitted was emitted during the first phase of the test (usually first hour of the test run). On the average, 46 percent of the total mass emitted during the entire run was emitted during the first phase of the test (23% of the total run time).

FIGURE 71

Particulate Emissions: First Phase Tests

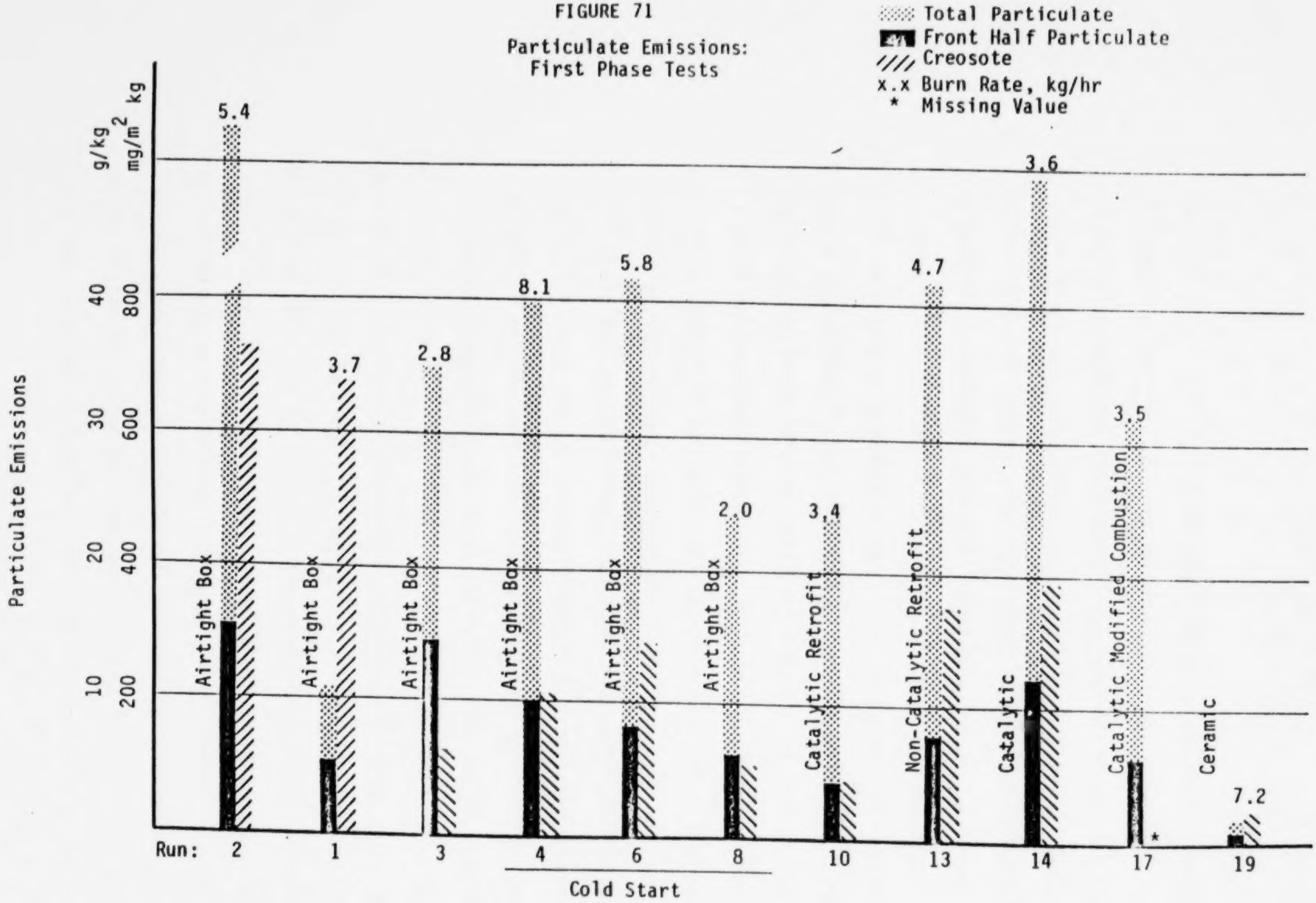


TABLE 40

Summary of Results:
Phase 1 Tests

RUN	FUEL CONSUMED		MASS EMITTED		CREOSOTE		PARTICULATE CONCENTRATION		MASS EMISSIONS	
	kg, Dry		g		mg		g/dscm		g/kg	
	P-1[a]	%[b]	P-1	%	P-1	%	P-1	P-2[c]	P-1	P-2
1	9.3	50	47	25	56	35	0.8	1.7	11	33
2	8.3	38	260	48	53	30	7.0	2.3	69	45
3	8.2	57	131	59	9	33	1.6	1.4	35	33
10	8.5	37	93	39	6	13	1.5	1.2	24	22
13	8.6	39	164	48	27	41	3.1	1.4	42	30
14	5.6	43	125	56	19	45	2.1	2.2	49	30
17	6.5	47	95	50	--	--	1.6	0.9	32	28
19	6.6	46	4.5	44	4	84	0.4	0.1	1.5	1.6
AVE		45		46						

[a] Phase 1

[b] Phase 1 ÷ total x 100

[c] Phase 2

Comparison of the cold start Phase 1 tests to the corresponding hot start tests (a total of three pairs of tests at three different fuel moisture contents) does not yield any discernable trend. Only three tests were conducted under each start condition and each of the three tests were conducted using different fuel moistures. In two of the three test pairs, the hot start generated higher particulate emissions. Carbon monoxide and hydrocarbon emissions were nearly the same. These results are summarized in Table 41.

TABLE 41

Results:
Cold Start vs Hot Start

RUN	FUEL MOISTURE	START PROCEDURE	BURN RATE	PARTICULATE EMISSIONS		CARBON MONOXIDE	HYDROCARBON
			kg/hr	g/kg	d/dscm	g/kg	g/kg
1[a]	Low	Hot	3.7	11	0.79	190	12.9
4	Low	Cold	8.1	40	3.57	210	11.9
2[a]	Med	Hot	5.4	69	7.01	150	12.9
6	Med	Cold	5.8	42	3.75	170	9.2
3[a]	High	Hot	2.8	35	1.55	210	9.8
8	High	Cold	2.0	24	0.89	190	11.1

[a] First test phase only.

EFFECT OF FUEL MOISTURE CONTENT

A series of tests on the airtight box stove were tested with the specific purpose of determining the effect of fuel moisture content on emissions. A total of six tests were conducted; two tests at three different moisture levels -- "dry, medium, and high" moisture. The protocol established that the moisture ranges of interest were: 15-20, 25-30, and greater than 40 percent, dry basis. Figure 72 graphically presents the particulate results obtained during the six emission tests. The objective was to operate the stove in a similar manner for all tests so that the only variable would be fuel moisture content. However, although an attempt was made to operate the appliance at a uniform burn rate for all tests, this attempt was not totally successful; burn rates varied from 1.9 to 2.9 kg/hr. The variation in fuel moisture likely contributed significantly to the inability to operate at a single standard burn rate. Nonetheless, the variation in burn rate does not seem to have a significant impact on interpretation of the results. One other signigfcant point regarding stove operation needs to be mentioned. In order to try and maintain a "low to medium-low" burn rate as established by the test protocol the stove was operated in a "dampered down" condition during the low moisture tests. With the low moisture wood, a very rapid combustion rate condition was immediately established; in order to control the burn rate, the air inlets were nearly totally closed. However, it is believed that this represents typical operation of an appliance by the homeowner, since this is the action which would normally be taken to control the heat output rate.

FIGURE 72

Particulate Emissions Results:
Fuel Moisture Tests

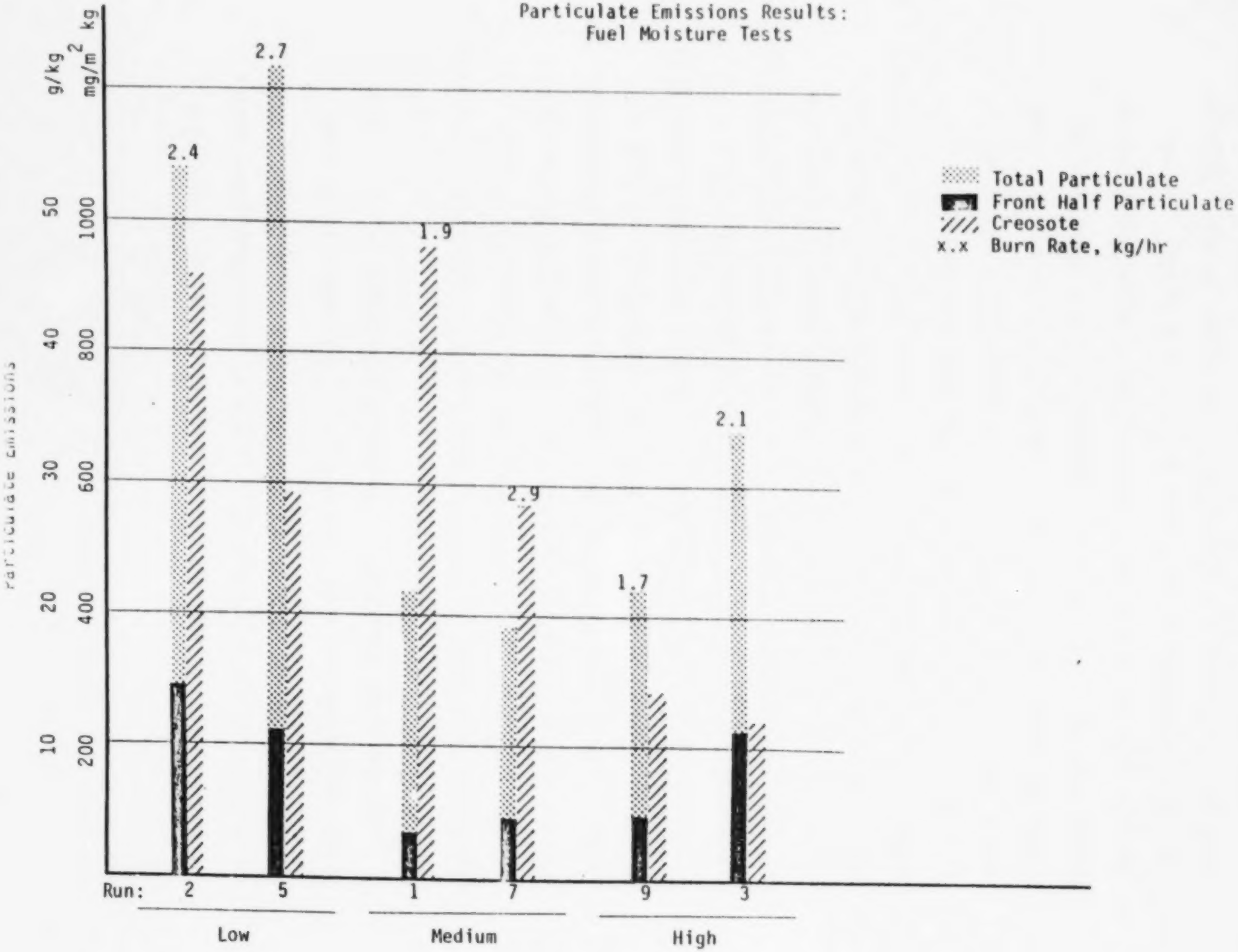


Figure 73 presents the emission results from the six tests graphed as a function of fuel moisture; Table 42 summarizes the data. Emission results are presented in terms of both g/kg and g/10^4 Btu. The low moisture fuel resulted in significantly higher emission levels than the medium moisture fuel. The high moisture fuel tests also resulted in higher emissions, but the increase in emissions was not nearly as great as with the dry fuel. Note that both dry moisture runs were conducted at higher burn rates than the low moisture tests (see Table 42); one would normally expect lower emissions at a higher burn rate. In Figure 68 , presented in the previous section, it is apparent that the low moisture test emissions are well above the level expected at the respective burn rates of the two tests. (For Run 2 at a burn rate of 2.4 kg/hr an emission rate of 20 g/kg is predicted as compared to the measured 54 g/kg. Similarly for Run 5 an emission rate of 18 g/kg is predicted as compared to the actual rate of 62 g/kg.) The data also were presented in terms of g/10^4 Btu in order to account for any difference in net efficiencies for the tests at different fuel moisture levels. The efficiency of the high moisture fuel tests was significantly lower than for the other test conditions; this results in a slight upward shift of the emissions, relative to the medium moisture fuel tests.

As previously mentioned, it was originally intended to conduct all tests at a single burn rate. Previously, in this report, it has been shown that emissions are dependent upon burn rate. To determine if the differences in burn rate among these runs might have a significant impact on interpretation of the results, the data were normalized to a single burn rate of 2.4 kg/hr. The data were normalized based on the relationship determined in this study.

$$y = 156\ e^{-.84x}$$

where y equals emissions, g/kg and x equals burn rate, kg/hr. The calculation used for determining the normalized emission rate is as follows:

$$En_i = \frac{y_{2.4}}{y_i} \times E_i$$

Where:

En_i = Normalized emission rate for run i

$y_{2.4}$ = Calculated emission rate for burn rate of 2.4 kg/hr

y_i = Calculated emission rate for actual burn rate of run i

E_i = Actual measured emission rate for run i

Table 43 summarizes the normalized emission rate data. Figure 74 presents the normalized emission rates as a function of fuel moisture content. Normalization of the data did not signficantly change the results. The emission rates for the high moisture fuel tests did decrease slightly in relation to the other fuel levels, since these tests were conducted at slightly lower burn rates than the normalized rate of 2.4 g/kg. However, basic conclusions are not changed.

Table 42 also presents the results for creosote, carbon monoxide, and hydrocarbons. A similar trend in emissions was not obtained for these three pollutants. In all these cases, the high moisture tests had the lowest emission rates (g/kg).

FIGURE 73

Particulate Emissions As A Function
of
Fuel Moisture

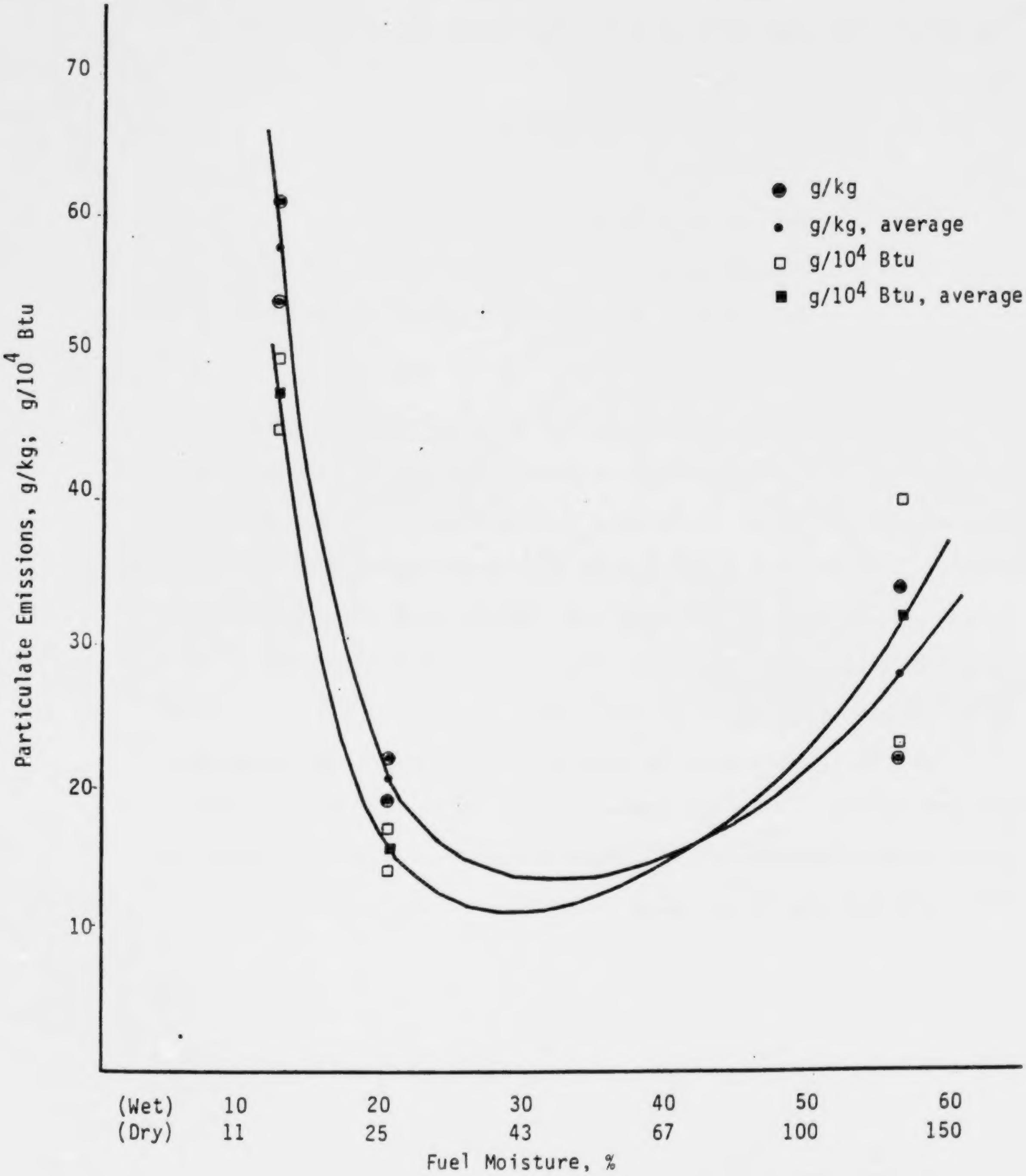


TABLE 42

Summary of Results: Fuel Moisture Tests

RUN	FUEL MOISTURE (%)		BURN RATE	PARTICULATE g/kg		CREOSOTE	CO	HC
	Wet	Dry	kg/hr	Total	Frt. Half	mg/m^2 kg	g/kg	g/kg
2	12	14	2.4	54	14	917	189	16.9
5	12	14	2.7	62	11	592	220	12.1
AVE	12	14	2.5	58	22	754	205	14.5
1	21	26	1.9	22	6.3	969	190	13.8
7	20	25	2.9	19	4.4	568	160	8.8
AVE	20	25	2.4	20	5.3	769	175	11.3
3	56	126	2.1	34	11	218	160	10.5
9	56	126	1.7	22	5	240	110	6.6
AVE	56	126	1.9	28	8	229	135	8.6
4	12	14	8.1	40	10	216	210	11.9
6	19	24	5.8	42	8	291	170	9.2
8	56	126	2.0	24	6	109	190	11.1

FIGURE 74

Particulate (Normalized Burn Rate) Emissions
As A Function of
Fuel Moisture

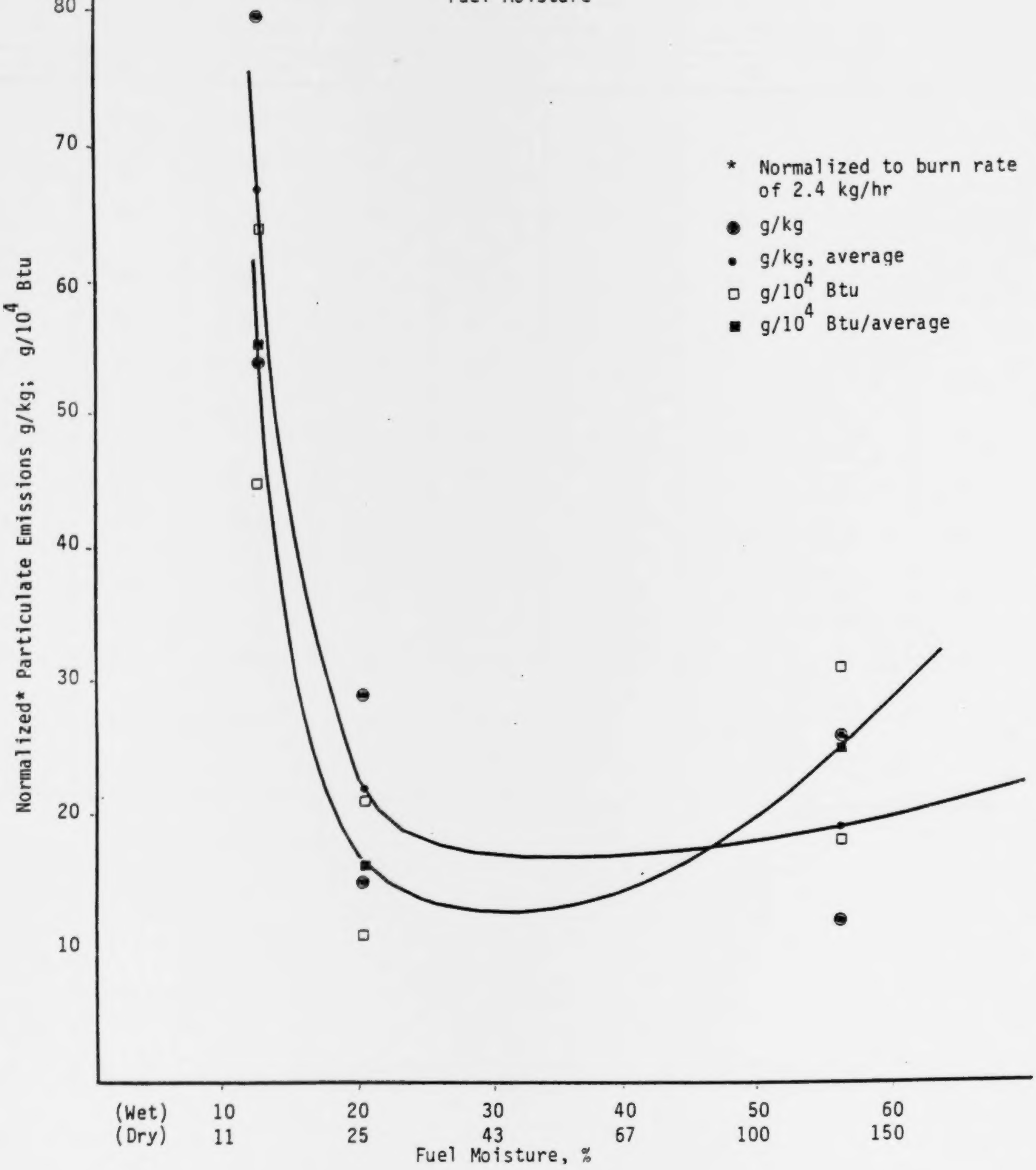


TABLE 43

Normalized* Particulate Results:
Fuel Moisture Tests

RUN	FUEL MOISTURE (%)		BURN RATE	TOTAL PARTICULATE EMISSIONS			
	Wet	Dry	kg/hr	g/kg	$g/10^4$ Btu	g/kg*	$g/10^4$ Btu*
2	12	14	2.4	54	45	54	45
5	12	14	2.7	62	50	80	64
AVE	12	14	2.5	58	42	67	55
1	21	26	1.9	22	17	15	11
7	20	25	2.9	19	14	29	21
AVE	20	25	2.4	20	15	22	16
3	56	126	2.1	34	40	26	31
9	56	126	1.7	22	23	12	18
AVE	56	126	1.9	28	31	19	25

* Normalized to Burn Rate of 2.4 kg/hour; see text for explanation of procedure.

Comparison of Results to Information in the Literature

Review of the literature indicates three other studies (two by Shelton[6,8] and one by Barnett[1a]) have information pertinent to the effect of fuel moisture content on emissions.

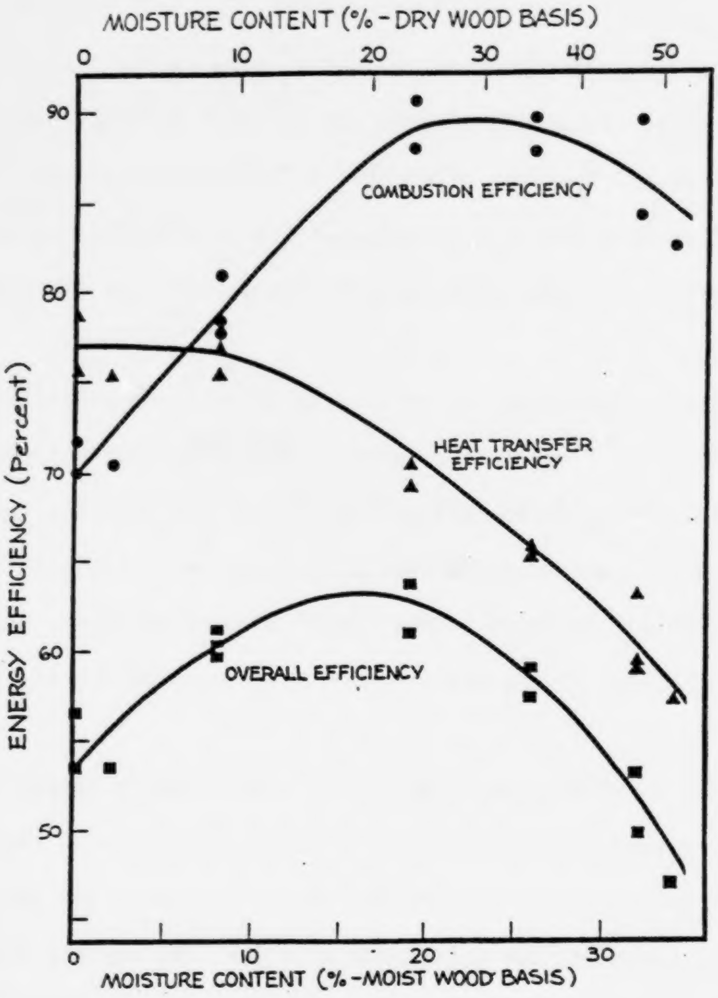
Shelton conducted two separate studies. In one study[6] he evaluated the impact on heat output efficiency as a function of fuel moisture. In the second study[8], he measured creosote accummulation as a function of fuel moisture content at several heat output rates. In both cases the tests were conducted with the objective of maintaining a constant heat output rate with the different fuels; this is an important consideration. Shelton's results generally indicate that higher emissions are expected with dryer fuel; the impact of wet fuel is less clear. In the study of heat output, higher emissions would be expected, but in the other study, lower creosote emissions were actually measured. These results are briefly discussed below.

Figure 75, summarizes the results Shelton obtained when measuring efficiencies as a function of fuel moisture content. Note that in this study emissions were not measured actually. However, if one assumes emissions are inversely correlated with combustion efficiency (a reasonable assumption), then these results indicate higher emissions at both low and high fuel moisture levels. Optimum performance (least emissions) would be expected either in the 25-35%, or 15-25% moisture range (dry basis) depending upon whether one expected emissions to be better correlated with combustion efficiency or overall efficiency. Just because the overall energy efficiency is greatest at 20 percent does not necessarily mean one should expect the lowest emissions at this point. The peak combustion efficiency was measured at 25-30 percent moisture; one might expect that the lowest emissions (g/kg) would occur at this point. Calculating emissions in terms of useable heat output (g/10^4 Btu), would likely shift the point of lowest emissions towards the point of greatest overall efficiency; however, how much of a shift to expect is not clear, and would be pure speculation, since the quantitative relationship between combustion efficiency, heat transfer efficiency, and mass of emissions is not apparent.

The results obtained during this study actually correlate quite well with Shelton's work. The minimum emission rate actually measured during this study occurred at 25 percent moisture (dry) although the function (graph) estimated from the three points measured would indicate minimum emissions occurring somewhere between 25-40 percent moisture. According to Figure 75 (Shelton's) one would expect minimum emissions at 25-30% moisture.

In Shelton's second study[8], emissions were actually measured by determining creosote accumulation over a period of days with the appliances operating at constant heat output for the test period. Six units were simultaneously operated, two units each with low, medium, and high moisture wood, 5, 25, and 50 (Oak), 33 (Pine), percent, dry basis for dry, medium and high moisture, respectively. Figures 76 and 77 summarize the results obtained by Shelton for pine and oak fuel respectively. With the exception of the tests conducted to simulate a fireplace (doors open and air inlets wide open) creosote decreased with increasing fuel moisture.

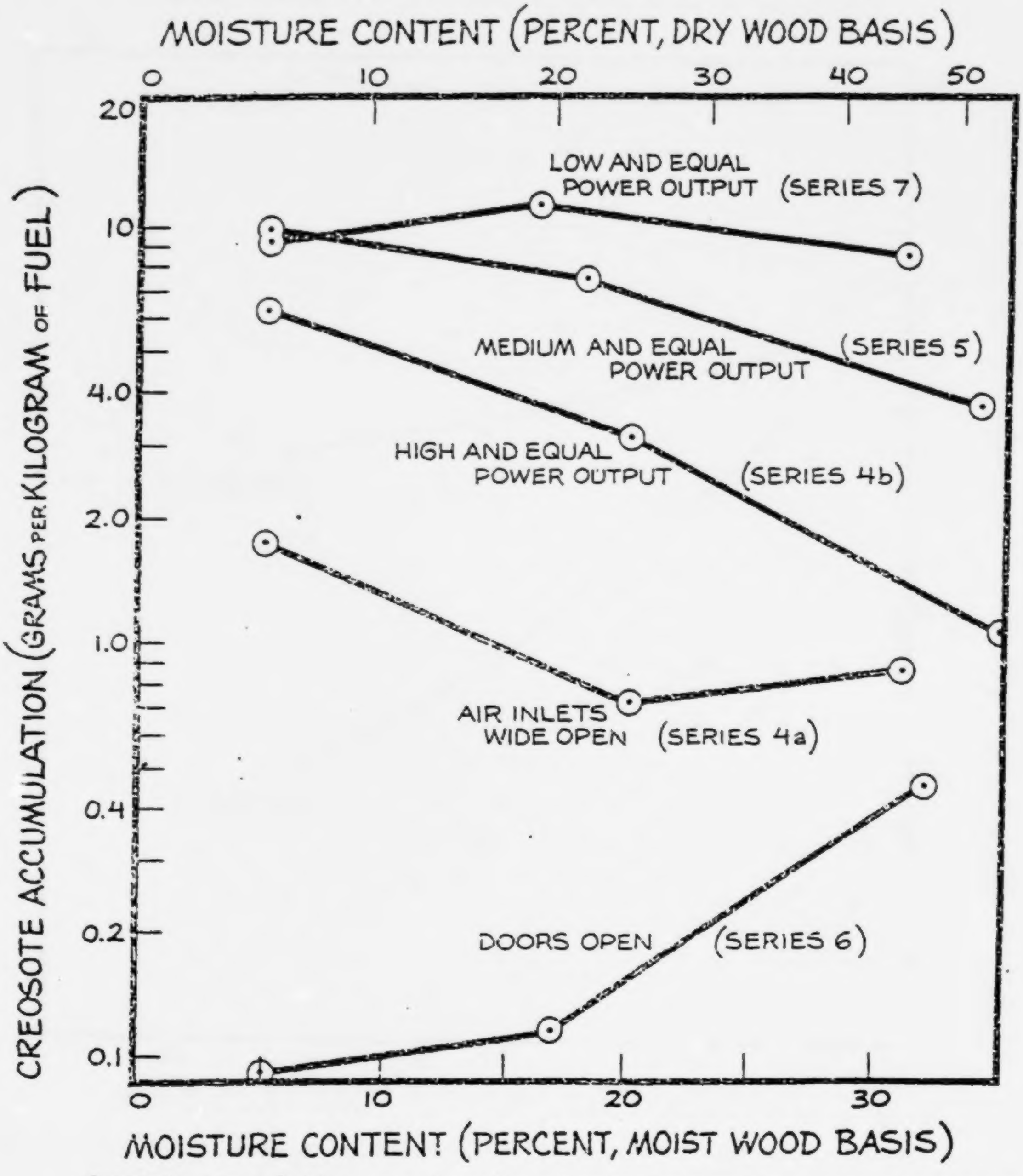
FIGURE 75



The dependence of efficiencies on fuel moisture content in an airtight stove. The air inlet setting was varied to maintain an average power output of about 17,000 Btu per hour for all moisture contents. The fuel load volume was approximately constant.

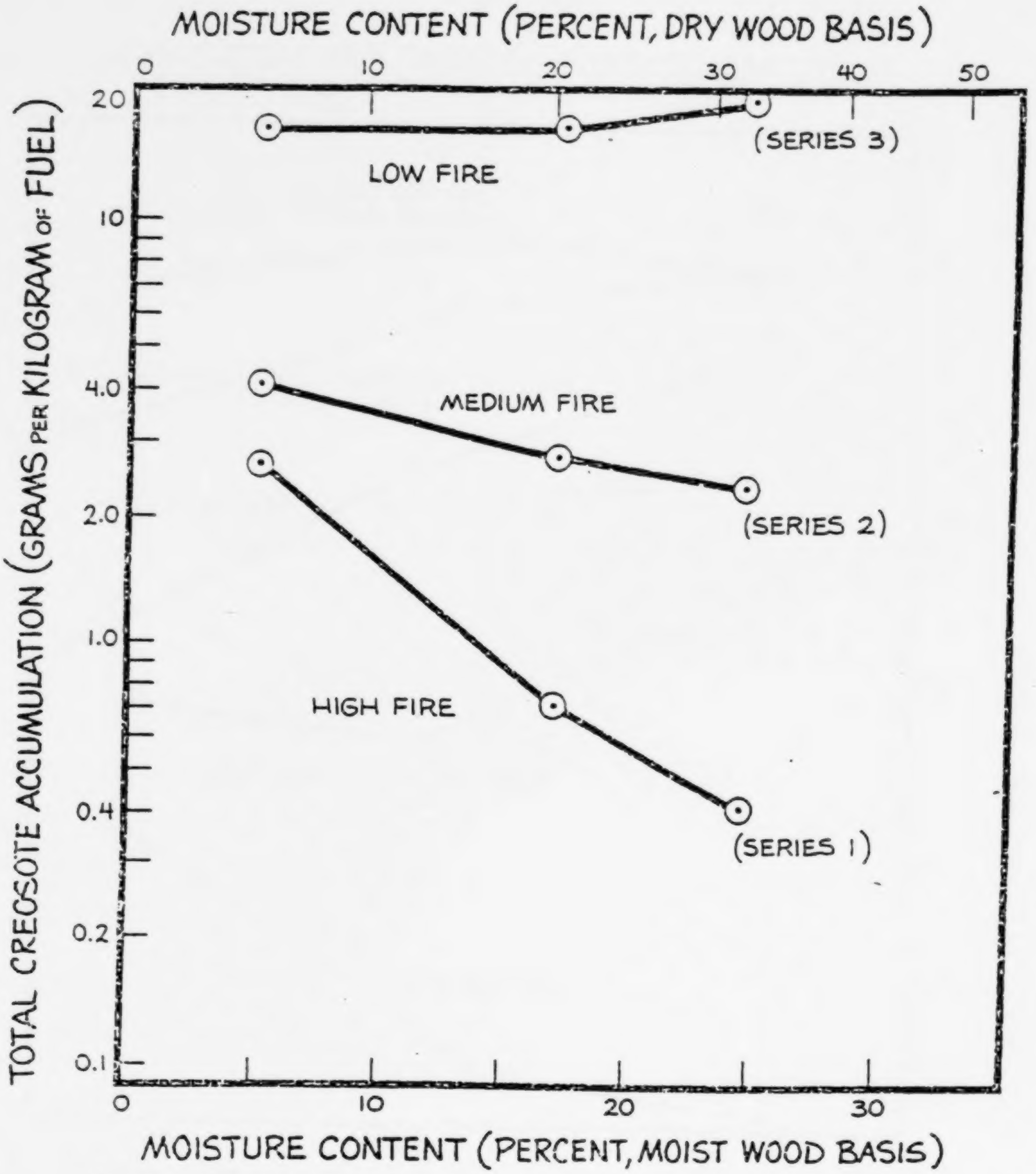
Source: Shelton[1c,6]

FIGURE 76



Creosote accumulation as a function of moisture content, using pinon as fuel.
Source: Shelton[8]

FIGURE 77



Creosote accumulation as a function of moisture content, using oak as fuel. Source: Shelton[8]

Shelton's results confirm the results of this study, that dry wood will cause increased emissions if a constant power output is maintained. The lower creosote deposition obtained with wet wood contradicts the results obtained during this study which indicate slightly higher emissions than with medium moisture wood would be obtained. However, during this study, the burn rate for the medium and low moisture fuel were maintained near constant (2.4 and 1.9 kg/hr, respectively) with the wet fuel tests actually being conducted at a slightly lower rate (increased emissions expected). On the other hand, in order to maintain a constant heat output, Shelton probably operated the low moisture fuel tests at a slightly higher burn rate (burn rate data not provided). A higher burn rate may help to explain the lower emissions for the wet fuel tests. This brings up an interesting point -- operation of the appliance is actually the major controlling factor; the impact of fuel moisture on emissions is largely due to the effect fuel moisture has on stove operation.

A point worth noting is the impact firing rate has on creosote formation, according to Shelton's work; this impact can be compared to the impact from fuel moisture. The greatest dependency of creosote deposition on combustion rate was noted for the oak fuel (Figure 77). Whereas the greatest variation in creosote due to fuel moisture (high fire series 1, low to high moisture) was 1.6 g/kg (2.0-0.4), or a factor of 4 times, the impact on creosote emissions from a change in high fire (series 1) to low fire (series 3) was 14 g/kg (17-3) or a factor of 6 times for dry fue; similarly for wet fuel the change in creosote deposition due to burn rate was 20 g/kg (20-0.2) or a factor of 50 times. Similar although not as dramatic results were obtained with pine. The maximum range in creosote emissions due to fuel moisture occurred for the high burn rate (series 4b) 5 g/kg whereas the variation due to burn rate between high fire (series 4b) and low fire (series 7) was 4 g/kg for dry wood and 10 g/kg for wet fuel.

A final point should be made regarding Shelton's results. A direct correlation between emissions emitted to the atmosphere and creosote deposition is not certain. Changes in excess dilution air, stack flue gas temperature, and stack gas volume might affect creosote deposition without affecting actual emissions to the atmosphere or vise-versa. Consequently, the discrepancy between Shelton's results for creosote and this studies results for measured particulate emissions may in fact not be totally inconsistent. Finally, the limited amount of emission data must be considered in drawing firm conclusions.

Barnett[1a] conducted two tests at different moisture levels in conjunction with a series of emissions tests. One test was conducted at a fuel moisture content of 24%, the other test at 3%. Fuel moisture for the standard test runs was 30-40%. Barnett shows a decrease in emissions with the very dry fuel which is contradictory to the results so far discussed. During Barnett's study, the dry fuel (24%) moisture indicated a slight increase in emissions. However, close examination of the data indicates that a significantly higher burn rate was used for the dry fuel tests. The burn rates for the 35, 24, and 3 percent tests were 1.1, 1.2, and 2.2 kg/hr, respectively. This would likely explain the lower emissions obtained with the 3 percent moisture fuel.

In conclusion, the optimum fuel moisture range appears to be 25-35%, dry basis. Dryer fuel is expected to cause increased emissions. The emissions expected for very wet fuel are less clear; this study indicates slightly greater emissions whereas Shelton's work[8] indicates less emissions (creosote deposition). However, the fact that more fuel has to be burned when wet fuel is used (due to the heat loss from vaporization of water) warrants using properly seasoned wood, even if no emission reduction is obtained.

SIMPLIFIED TEST PROCEDURES

Five basic emission parameters other than particulate emissions as measured by EPA Method 5 and Oregon DEQ Method 7 also were measured during this test program. The primary purpose for measuring these parameters was to determine if they could be utilized as a simplified procedure in lieu of Method 5 testing to evaluate particulate emissions from wood burning appliances. The parameters measured were: creosote deposition, carbon monoxide concentration, gaseous hydrocarbon concentration, stack gas opacity, and smoke spot density. With the exception of smoke spot density, all parameters correlated to some degree with measured particulate emissions. The results for each of the five test parameters are separately discussed in this section.

Creosote Deposition

Table 44 summarizes the creosote deposition results. Creosote was measured at two locations within the stack; results from both locations are reported in terms of mass of creosote per unit area per kiligram fuel consumed (mg/m^2 kg).

In general, the correlation between the measurements taken at the two locations was not particularly good. Figures 78 and 79 graphically present the correlation between the two test locations graphed by test run and test phase, respectively. In Figure 78, the correlation has a slope of nearly 1 (.92) indicating that one would not expect a particular bias from either measurement; however, the correlation coefficient is only 0.62 indicating a great deal of scatter and imprecision in the results. Even a poorer correlation is obtained when evaluating the results for each test phase. This simply indicates that combining

TABLE 44

Creosote Results

RUN	CREOSOTE, mg/m^2 kg			PARTICULATE, g/kg	
	Transmissometer Location	Sample Location	Average	Total	Front Half
1-1	479	886	683	11	5.1
1-2	-	1051	1051	33	9.0
1	-	969	969	22	6.3
2-1	893	557	725	69	16.0
2-2	458	1619	1038	45	13.0
2	618	1217	917	54	14.0
3-1	159	89	124	35	14.0
3-2	578	110	344	33	6.5
3	337	98	218	34	11.0
4	167	264	216	40	10.0
5	508	676	592	62	11.0
6	292	290	291	42	8.3
7	748	388	568	19	4.4
8	190	27	109	24	6.1
9	331	148	240	22	4.8
10-1	25	136	81	24	3.9
10-2	191	421	306	22	3.7
10	130	316	223	22	3.7
11	193	187	190	17	3.3
12	221	324	273	38	7.4
13-1	289	409	349	42	8.1
13-2	174	484	329	30	4.8
13	219	455	337	35	6.1

TABLE 44 (Cont.)

RUN	CREOSOTE, mg/m^2 kg			PARTICULATE, g/kg	
	Transmissometer Location	Sample Location	Average	Total	Front Half
14-1	300	478	389	49	12.0
14-2	236	505	371	30	3.7
14	264	493	379	38	5.9
15	209	337	273	23	4.8
16	108	67	88	14	3.5
17-1	-	-	-	30	6.1
17-2	-	-	-	28	5.4
17	308	325	317	30	5.7
18	16	95	56	1	0.6
19-1	8	93	51	1.5	0.80
19-2	11	5	8	1.6	0.70
19	9	45	27	2	1.0

FIGURE 78

Creosote:
Transmissometer vs Sample Location
(By Test Run)

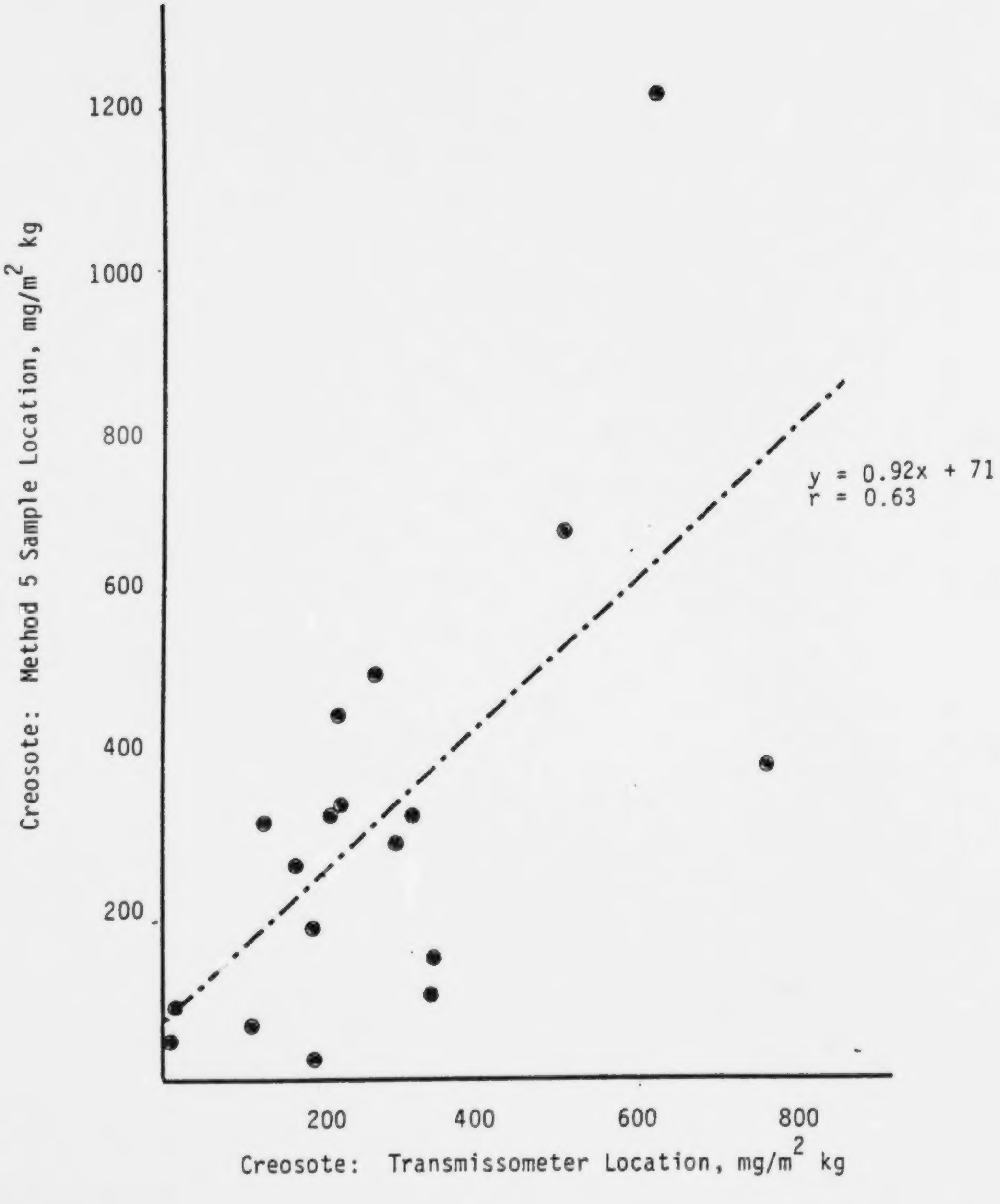
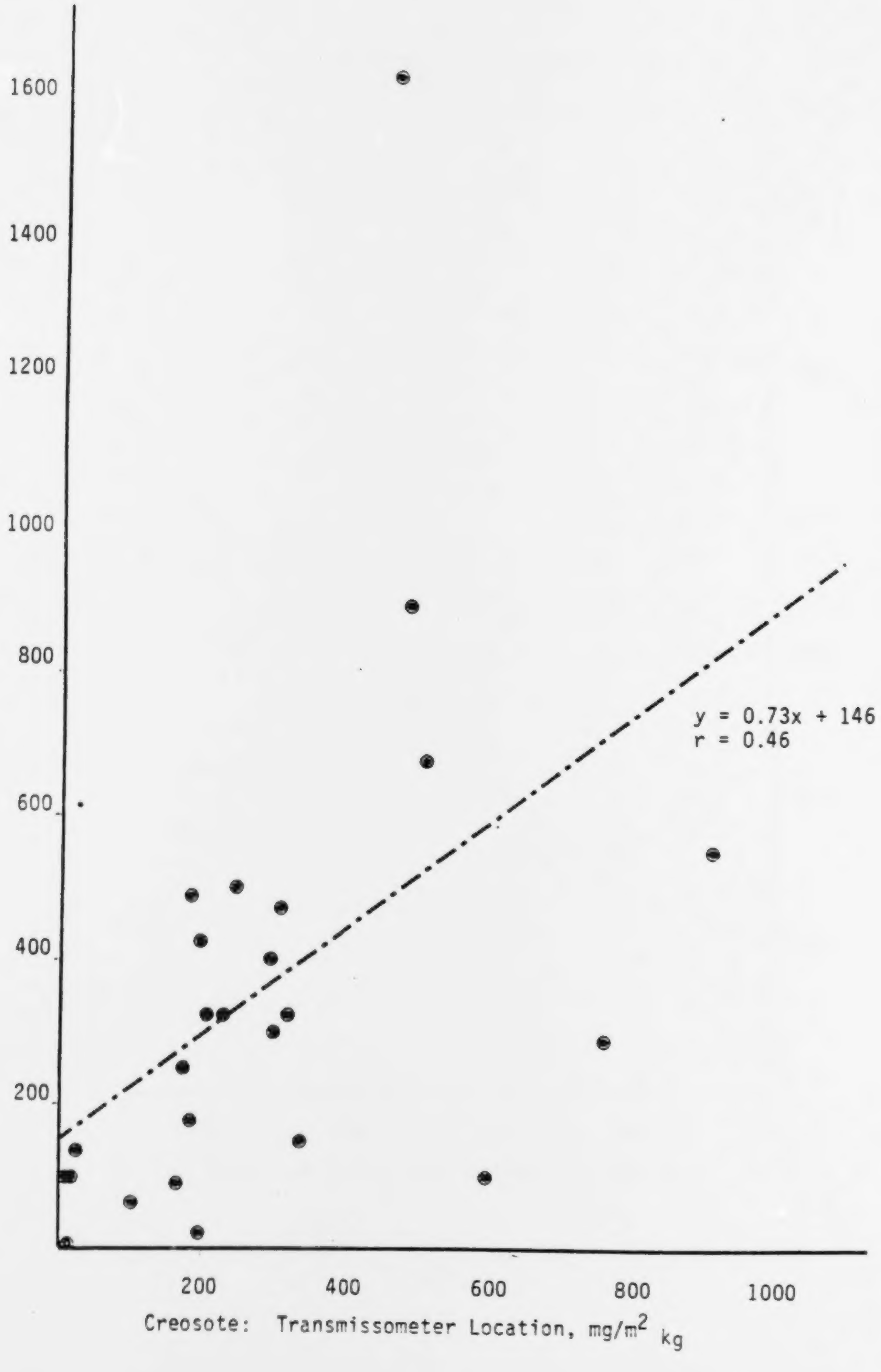


FIGURE 79

Creosote:
Transmissometer vs Sample Location
(By Test Phase)



(averaging) the test phase results to obtain a single result for each run, resulted in increasing the precision, as would be expected. The major question these data pose is whether the lack of precision is due to the measurement technique used (experimental error) or in fact, is inherent in the method, in that the creosote deposition varies randomly from point-to-point in the stack and from run-to-run.

Nonetheless, despite the poor precision obtained, a useful correlation does exist between the creosote deposition and the measured particulate emission rates. Figures 80 through 83 present correlations for creosote deposition and particulate emissions for four different cases: total particulate emissions versus creosote measured at the transmissometer location, the sample location, and the arithmetic average of the two measurements. In addition, the transmissometer location creosote measurement is correlated with front-half particulate. Note that in each of the figures, two correlation lines are presented, and one or two data points are highlighted by a star. These one or two data points appeared to be inconsistent with the rest of the data. Correlations are presented both including these data points and deleting these data points. Deletion of these data points has a dramatic impact on the correlation, resulting in a change in the correlation coefficient from 0.55 to 0.85. All correlations are based on creosote measurements by test run (as opposed to by test phase) unless otherwise noted.

The correlation of the transmissometer location with the measured particulate emissions was better than the creosote at the sample location. This could be for any number of reasons including random error, more turbulent flow conditions at the sample location, less uniform temperature,

FIGURE 80

Creosote
vs
Particulate Emissions
(Transmissometer Location)

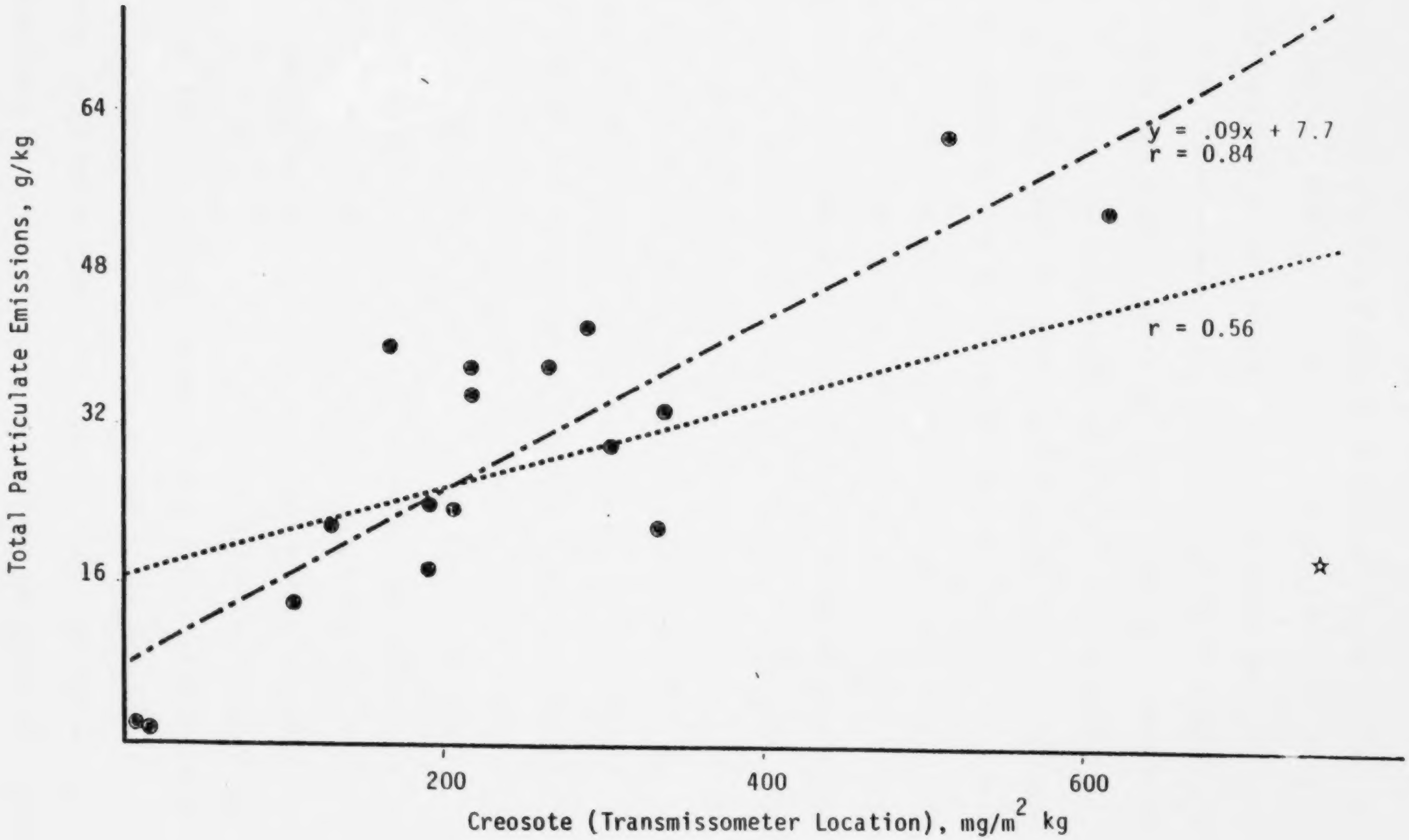


FIGURE 81

Creosote vs Particulate Emissions
(Sample Location)

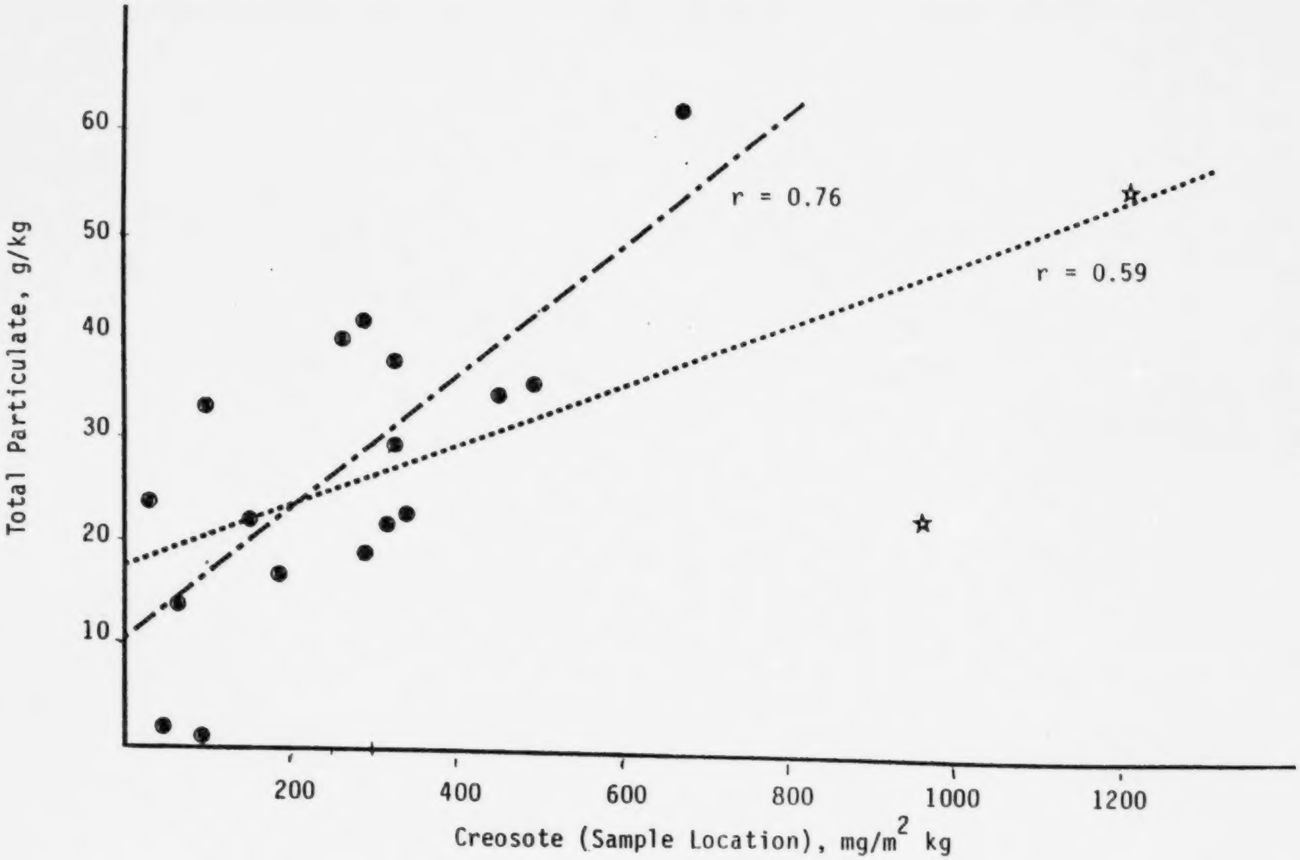


FIGURE 82

Creosote vs Particulate Emissions

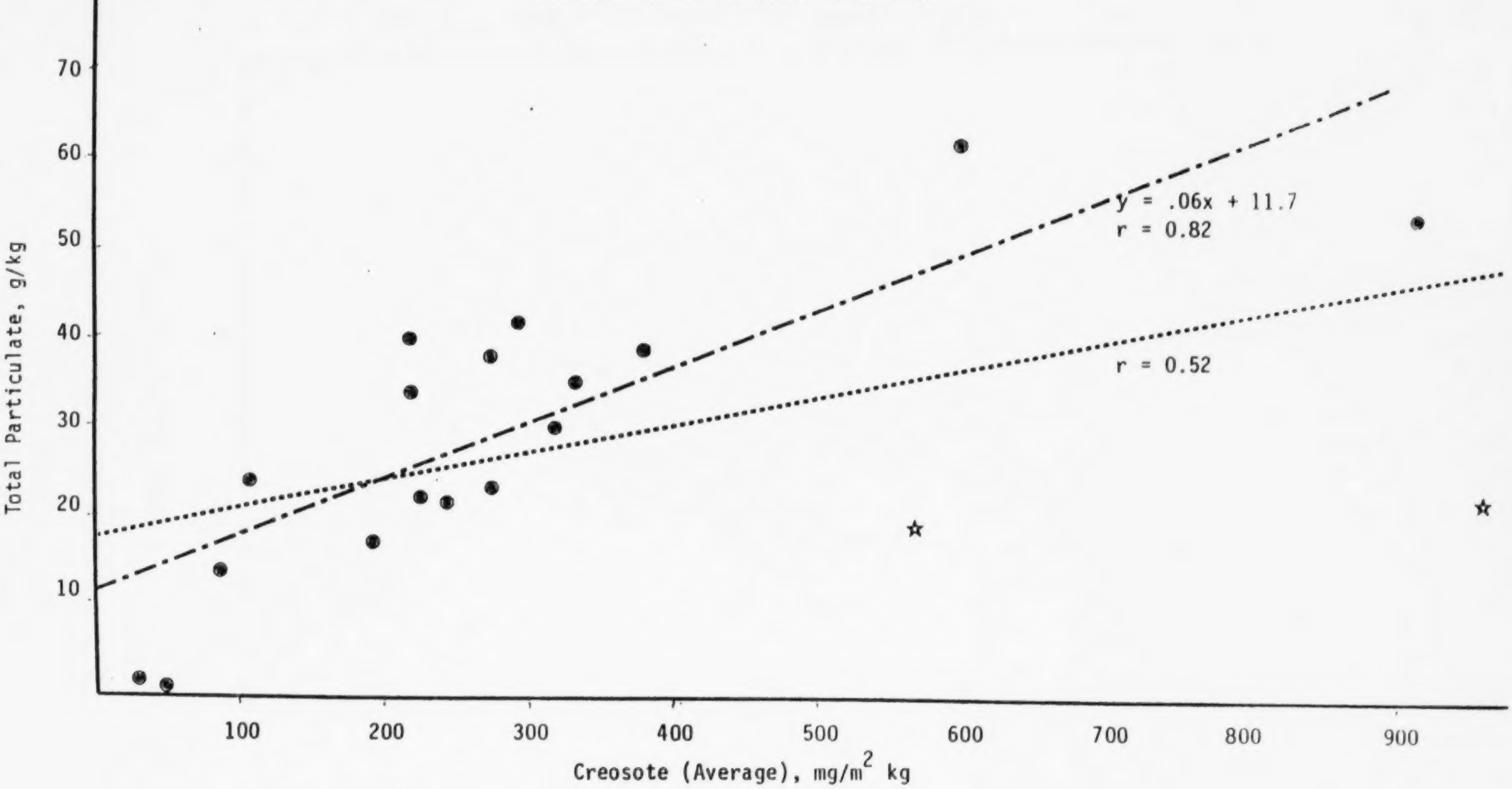
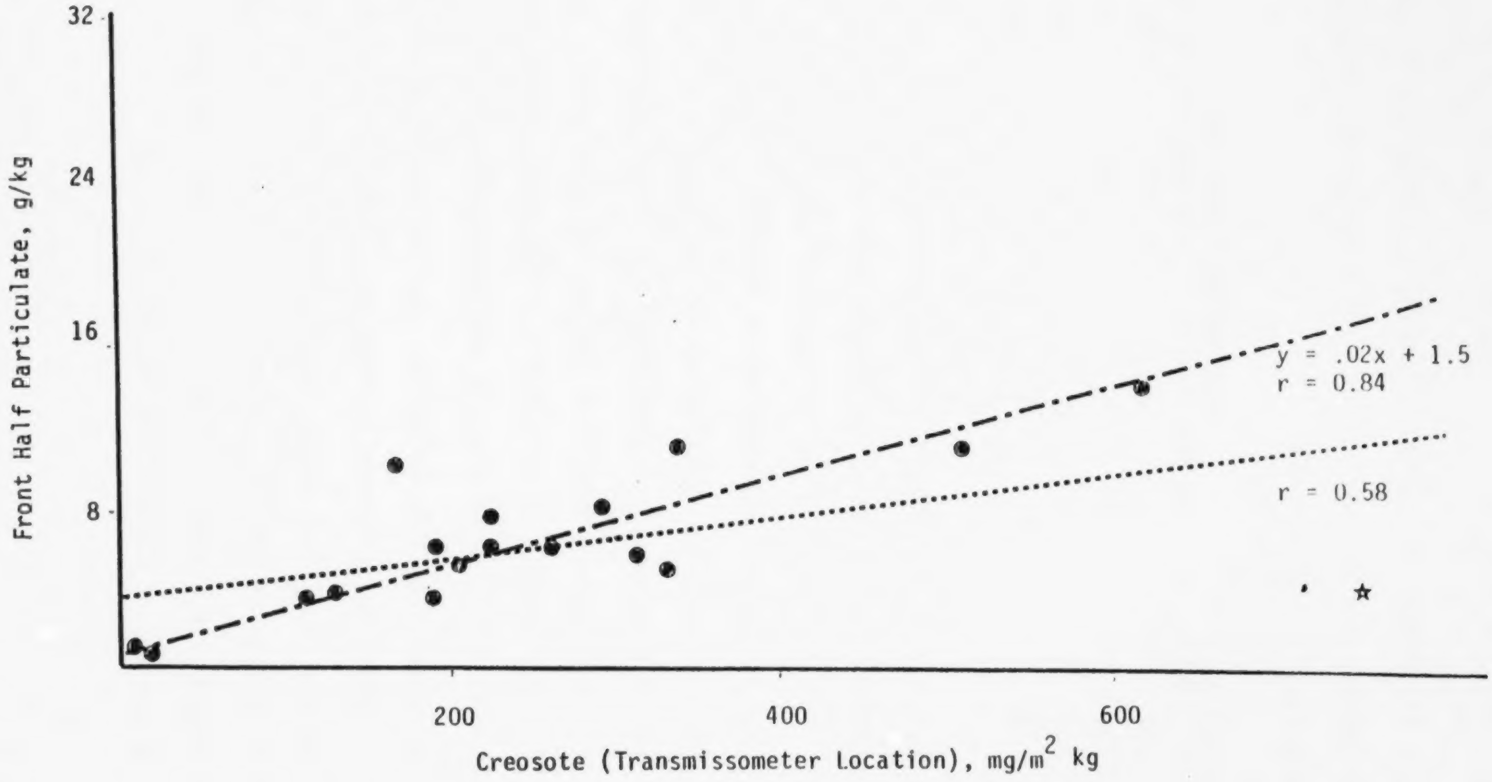


FIGURE 83

Creosote
vs
Front Half Particulate



etc.. Regardless, the expected results one would obtain from the three correlations for total particulate are actually very similar especially at the lower creosote levels:

Creosote (mg/m^2 kg)	Expected Emissions, g/kg Transmissometer	Sample	Average
100	17	17	18
300	34	30	31
500	52	43	43
700	70	56	56

As a matter of interest, a theoretical calculation was conducted to determine how the measured creosote collected on the test coupons would translate to deposition on a surface area equivalent to a 15-foot stack. These results are reported in Table 45. The total grams of creosote that would be deposited on the surface area of a 15-foot, 8-inch diameter stack assuming uniform deposition on the entire stack surface equal to the measured deposition (mg/m^2) was calculated. See Appendix A #31 for calculations. This theoretical deposition (grams) was then compared to the total particulate and condensible particulate (back-half of sample train) emitted during the test run to determine the theoretical percent deposition (reported in last two columns of Table 45, respectively). The creosote deposition ranged from 1.3 to 13 percent of the total emissions, with an average of 4.5 and a median of 3.1 percent. The creosote deposition ranged from 1.8 to 32 percent of the condensible particulate emissions with an average of 6.9 and a median of 3.7 percent.

TABLE 45

Creosote Deposition
Theoretical Percent of Total Emissions

RUN	PARTICULATE MASS EMITTED, g		CREOSOTE DEPOSITION		DEPOSITION[d], %	
	Total	Condensible[a] Fraction	$\frac{\text{mg}}{\text{m}^2\ \text{kg}}$[b]	g[c]	Total	Condensible
1	187	134	969	24.7	13	18
2	530	400	917	27.4	5.1	6.8
3	219	147	218	4.2	1.9	2.9
4	191	145	216	3.1	1.6	2.1
5	583	482	592	16.9	2.9	3.5
6	188	151	291	3.9	2.1	2.6
7	180	138	568	16.2	9.0	11.8
8	129	96	109	1.7	1.3	1.8
9	114	89	240	3.8	3.3	4.2
10	226	188	223	7.0	3.1	3.7
11	152	122	190	5.3	3.5	4.4
12	405	326	273	8.6	2.1	2.6
13	347	287	337	10.1	2.9	3.5
14	221	187	379	6.7	3.0	3.6
15	125	99	273	4.6	3.7	4.6
16	82	62	88	1.6	2.0	2.6
17	185	150	317	6.0	3.2	4.0
18	9.2	3.4	56	1.1	12	32
19	7.5	3.9	27	0.66	9	17

[a] Sampling Train Back-half catch

[b] Creosote measured during test

[c] Calculated total deposition on stack
15 ft length by 8 inch diameter

[d] Creosote deposition ÷ Particulate Mass x 100

Carbon Monoxide

Carbon monoxide was continuously monitored during each test run; data were recorded at 5 minute intervals. An average carbon monoxide (CO) concentration was calculated for each test run. These results were compared to the measured particulate emissions to determine if a relationship existed. Figure 84 presents total particulate concentration (g/dscm) as a function of carbon monoxide concentration, %. A linear correlation with a coefficient of 0.87 is obtained. However, this has limited value since the correlation for particulate is in terms of concentration; in order to obtain an emission rate, (g/hr, g/kg, or g/Btu) one needs to know the stack gas volumetric flow rate. The volumetric flow rate can be calcuated based on a carbon balance if carbon dioxide and the mass of fuel consumed also is measured. This calculation would assume all carbon is accounted for in the CO and CO_2 which is not totally accurate. A more useful correlation would be for particulate emissions, g/kg, directly as a function of CO concentration. However, it is obvious that the amount of excess air will affect the CO concentration measurement, but not the measured particulate emission rate, g/kg. Consequently, a correlation would be expected only if the CO concentration is first corrected for excess air. Figure 85 presents total particulate emissions as a function of adjusted CO concentration. In this case, the correction applied is based on the ultimate CO_2 concentration (CO_2 concentration expected for complete combustion of wood at zero percent excess air) and the actual measured CO_2 concentration. This factor essentially corrects the CO concentration to a zero percent excess air basis. Other correction functions also could be used such as calculated percent excess air (this

FIGURE 84

Total Particulate Concentration
vs
Carbon Monoxide Concentration

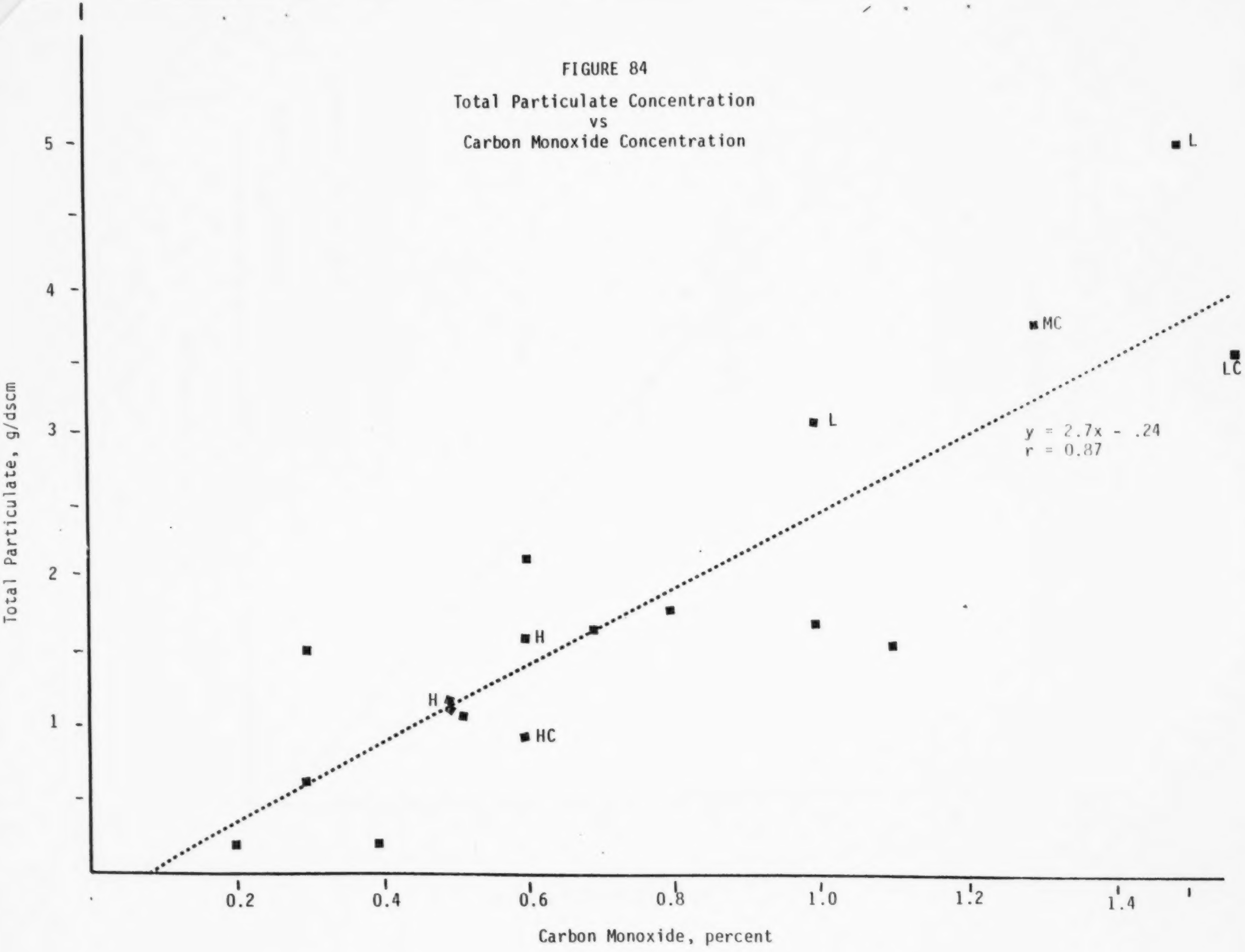
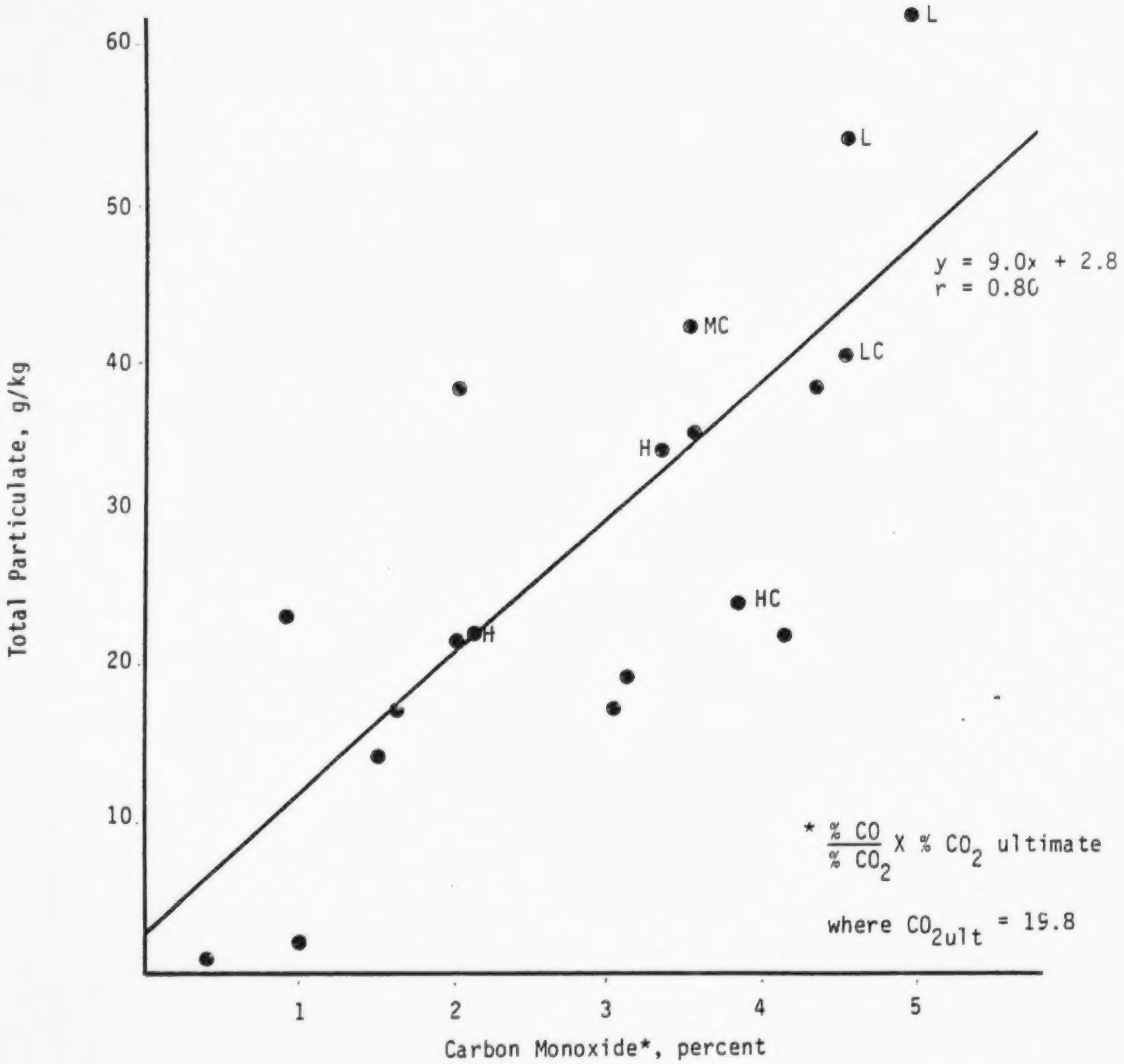


FIGURE 85

Particulate Emissions
vs
Adjusted* Carbon Monoxide Concentration

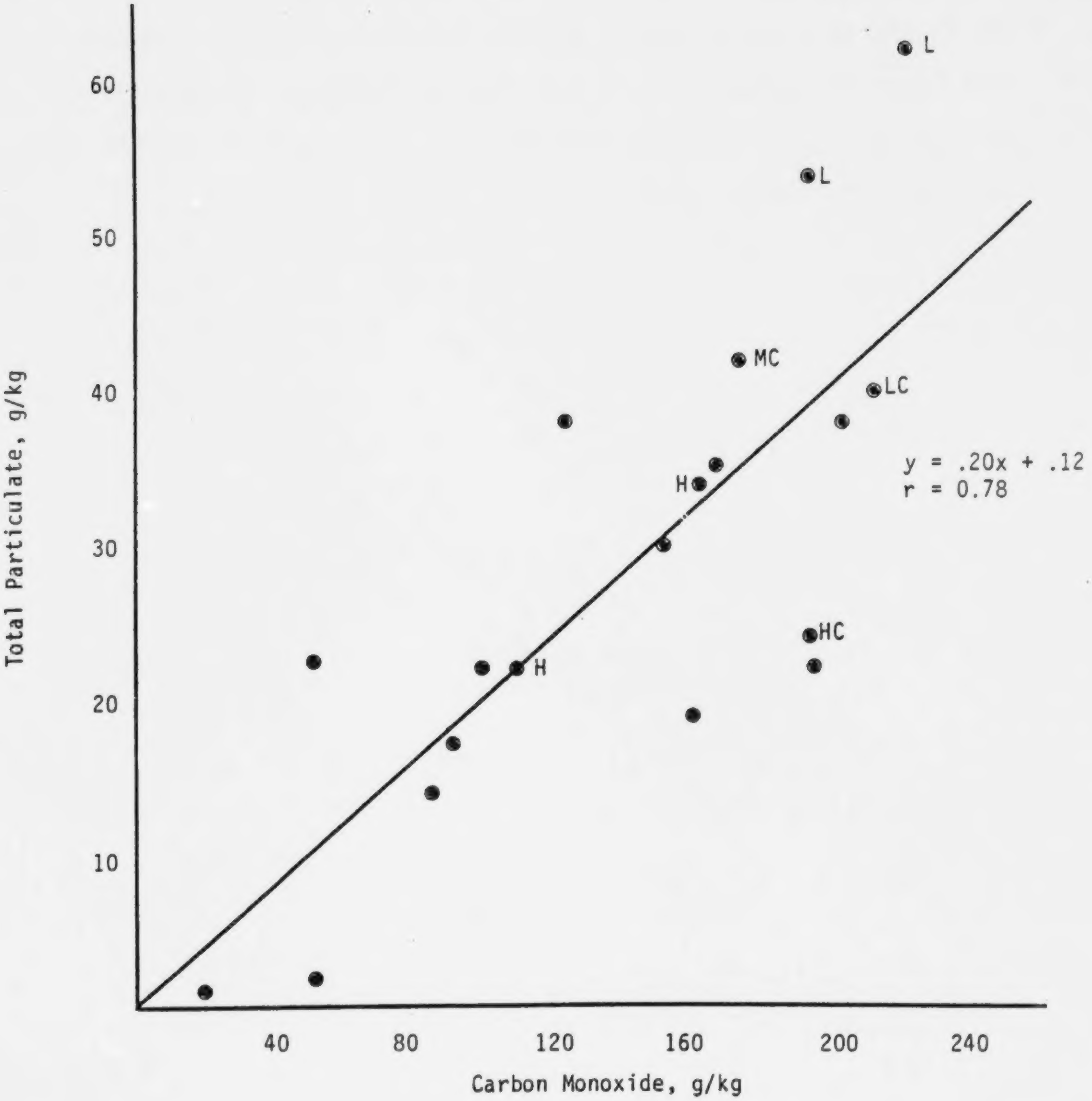


factor requires oxygen also be measured). As indicated in Figure 85 using the ultimate CO_2 correction, a reasonable correlation is obtained between total particulate emissions and CO concentration.

Figure 86 presents total particulate emissions (g/kg) as a function of CO emissions (g/kg). This is presented as a matter of interest; this correlation also requires that volumetric flow be measured in order to calculate the emission rates.

FIGURE 86

Particulate Emissions vs Carbon Monoxide



Gaseous Hydrocarbons

Gaseous hydrocarbons were continuously measured using a non-dispersive infrared analyzer. The emissions were measured as hexane (i.e., the monitor was calibrated with Hexane). Data from the monitor were recorded at 5-minute intervals and an average hydrocarbon concentration was then calculated for each test run.

In Figure 87 total particulate concentration is presented as a function of hydrocarbon concentration. A linear correlation with a coefficient of 0.86 is obtained. As previously mentioned regarding CO, the concentration correlation is of limited value since volumetric flow rate must be determined in order to obtain results in terms of emission rates. Figure 88 presents the correlation obtained when the hydrocarbon concentration is adjusted to account for dilution by excess air. The correction factor used is the ratio of the ultimate CO_2 to the measured CO_2. Figure 89 presents total particulate emissions (g/kg) as a function of hydrocarbon emissions (g/kg); again use of this correlation requires that volumetric flow rate be measured.

Although reasonable correlations are obtained using the gaseous hydrocarbon emissions, these correlations may be of limited use due to the unknown sensitivity of instrument response to different hydrocarbon compounds. Both Non-Dispersive Infrared (NDIR) and Flame Ionization Detectors (FID) (but especially the NDIR), have a varying response to different organic species. Consequently, a significant variation in response might be obtained from stove to stove or test to test depending on test conditions and the organic species emitted. The degree of variation expected is unknown; this may not be a major problem. Nonetheless,

FIGURE 87

Particulate Concentration
vs
Gaseous Hydrocarbon Concentration
(By Run)

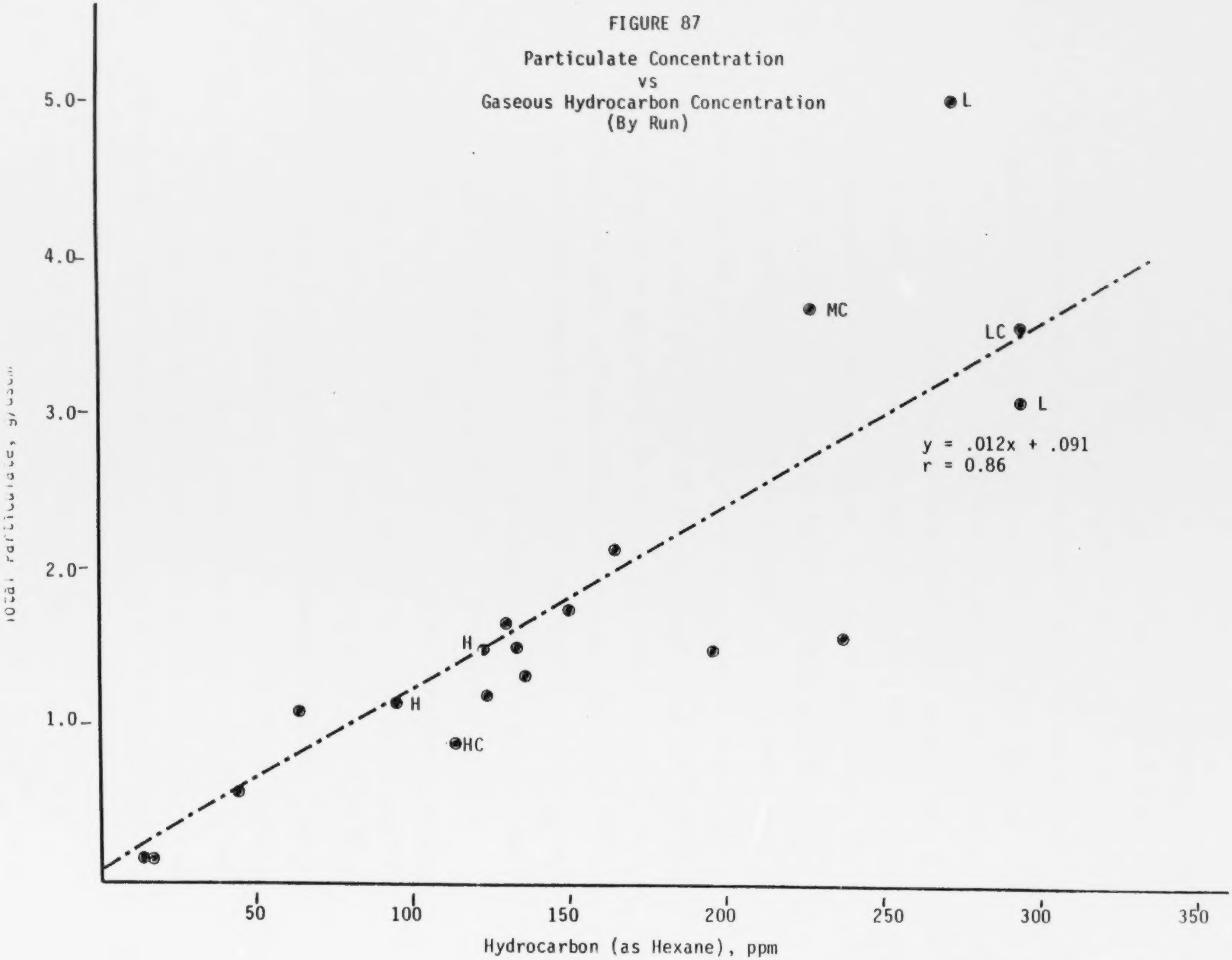


FIGURE 88

Particulate Emissions
vs
Adjusted Gaseous Hydrocarbon Concentration*

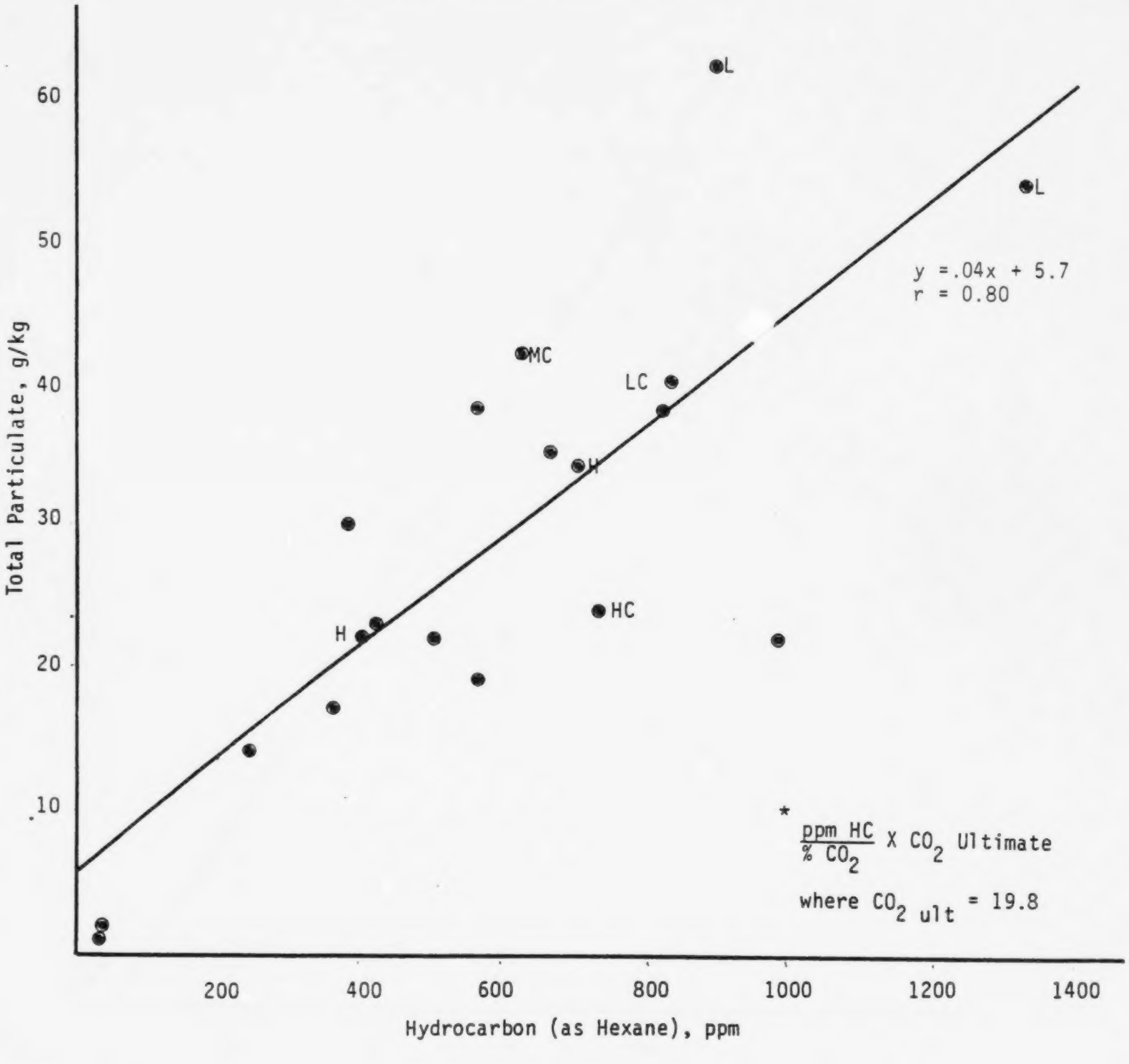
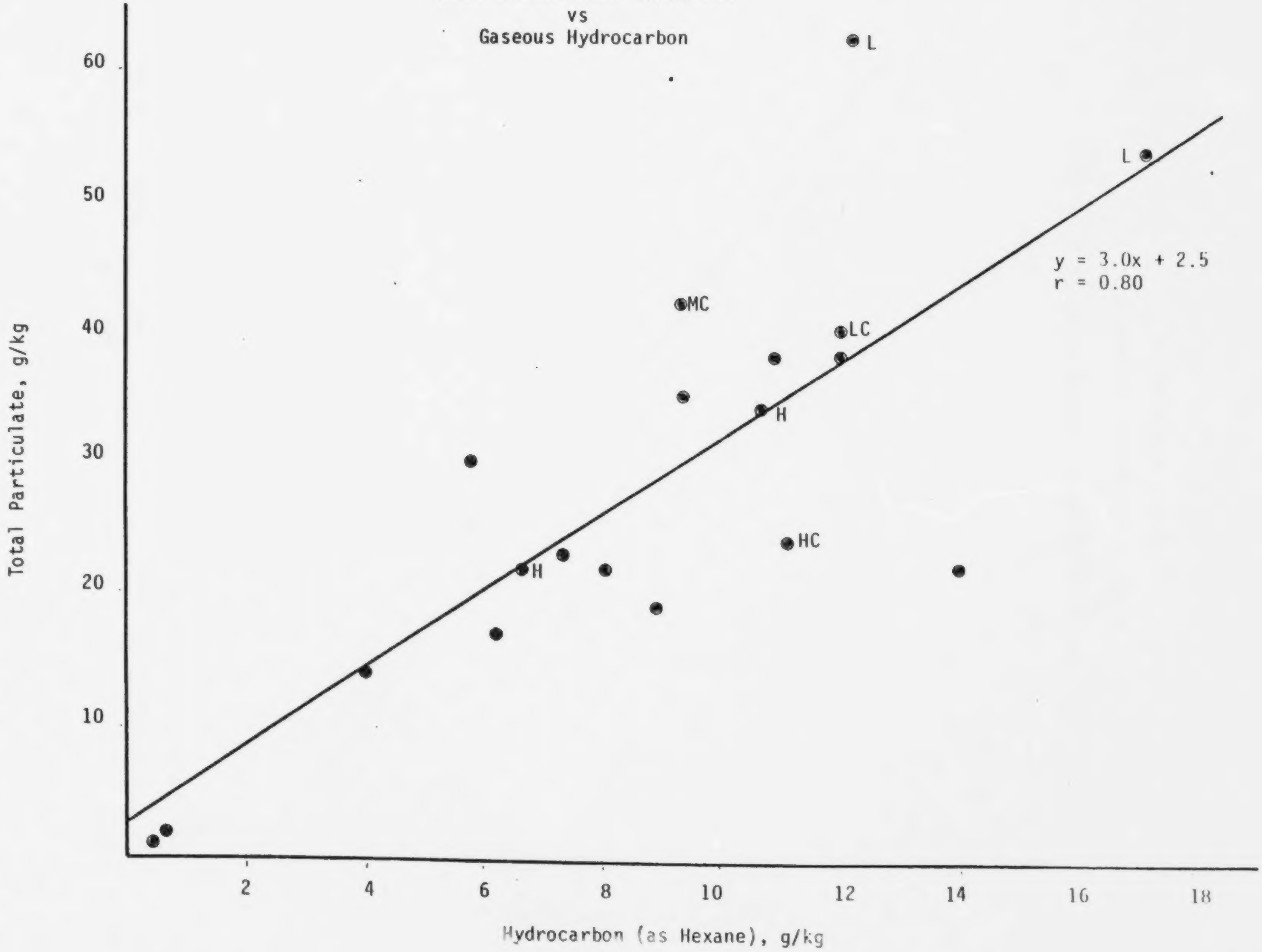


FIGURE 89

Total Particulate Emissions
vs
Gaseous Hydrocarbon



the measurement of hydrocarbons certainly should be useful for monitoring and measuring instantaneous changes in appliance emissions. Although some variation in system response might be expected, the data indicate that a relationship does exist between HC concentration and particulate; consequently, the HC analyzer would serve well as a real time monitor for emissions. In any event, in order to minimize this phenomenon use of an FID is recommended when measurement of gaseous emissions is desired.

Opacity

Opacity was measured by two methods-- visual observation and transmissometer. Visual observations were taken for discrete periods ranging from five to thirty minutes during each test run. Transmissometer measurements were continuously recorded on a strip chart; in addition, readings were recorded at 5-minute intervals. Figure 90 presents both the average (time weighted) observer opacity and average transmissometer opacity as functions of total particulate concentration (g/dscm). As previously mentioned, a correlation based on particulate concentration is of limited use unless volumetric flow rate also is measured. However, there is no simple correction factor for opacity for dilution due to excess air. Consequently, measurement of opacity is probably best correlated to concentration. Figure 91 presents opacity (observer and transmissometer) as a function of total particulate emissions, g/kg. A linear correlation is apparent. However, a significant spread in the data exists, especially in the 10-30 percent opacity range.

Table 46 presents a summary comparing observer and transmissometer data by run. For most runs the measured opacities for the two methods compared well. Visual observations were not made continually throughout the run; consequently, the reported value represents the average value for the periods observed only.

FIGURE 90

Total Particulate Concentration
vs
Opacity

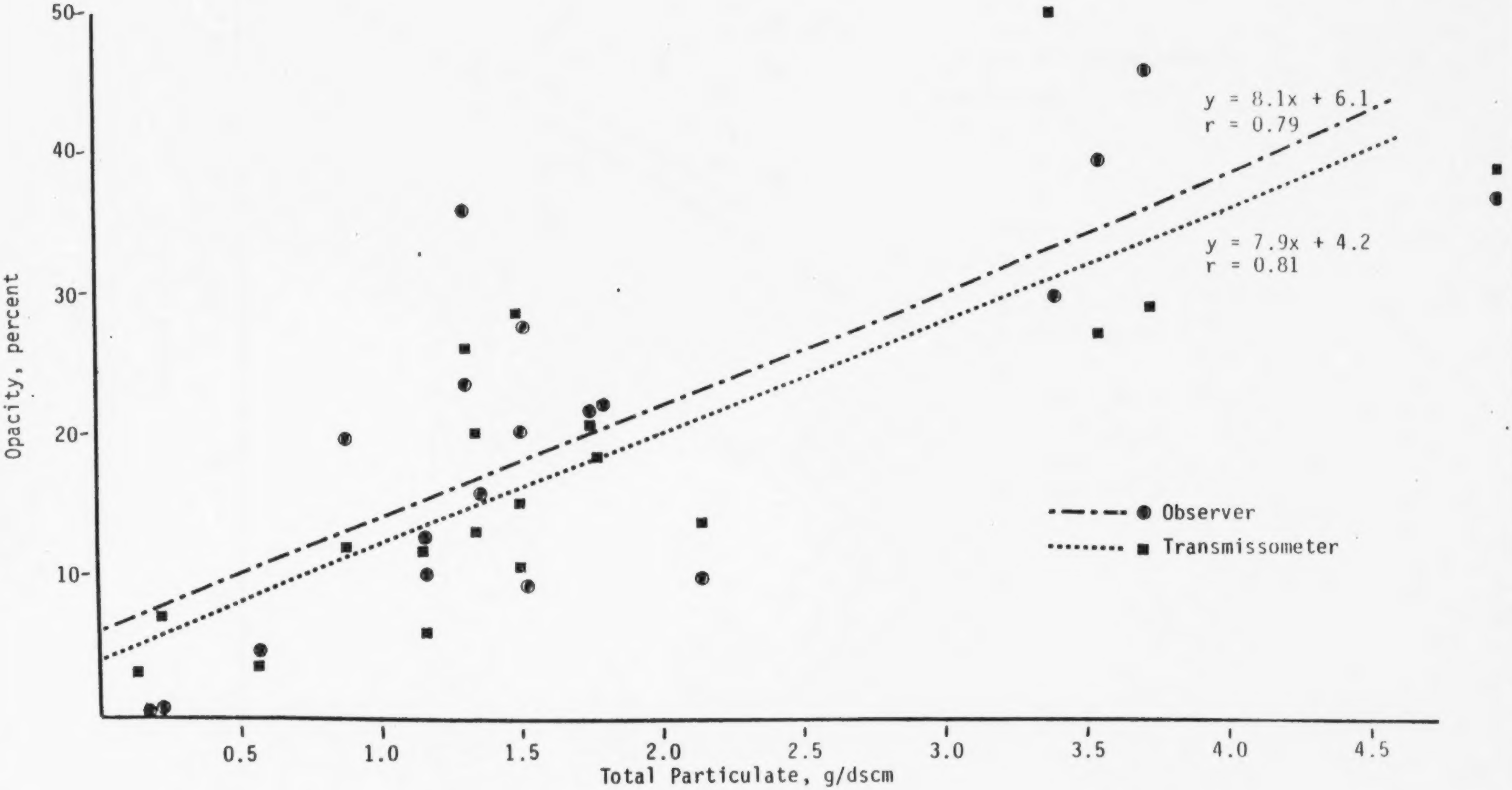


FIGURE 91

Total Particulate Emissions
vs
Opacity

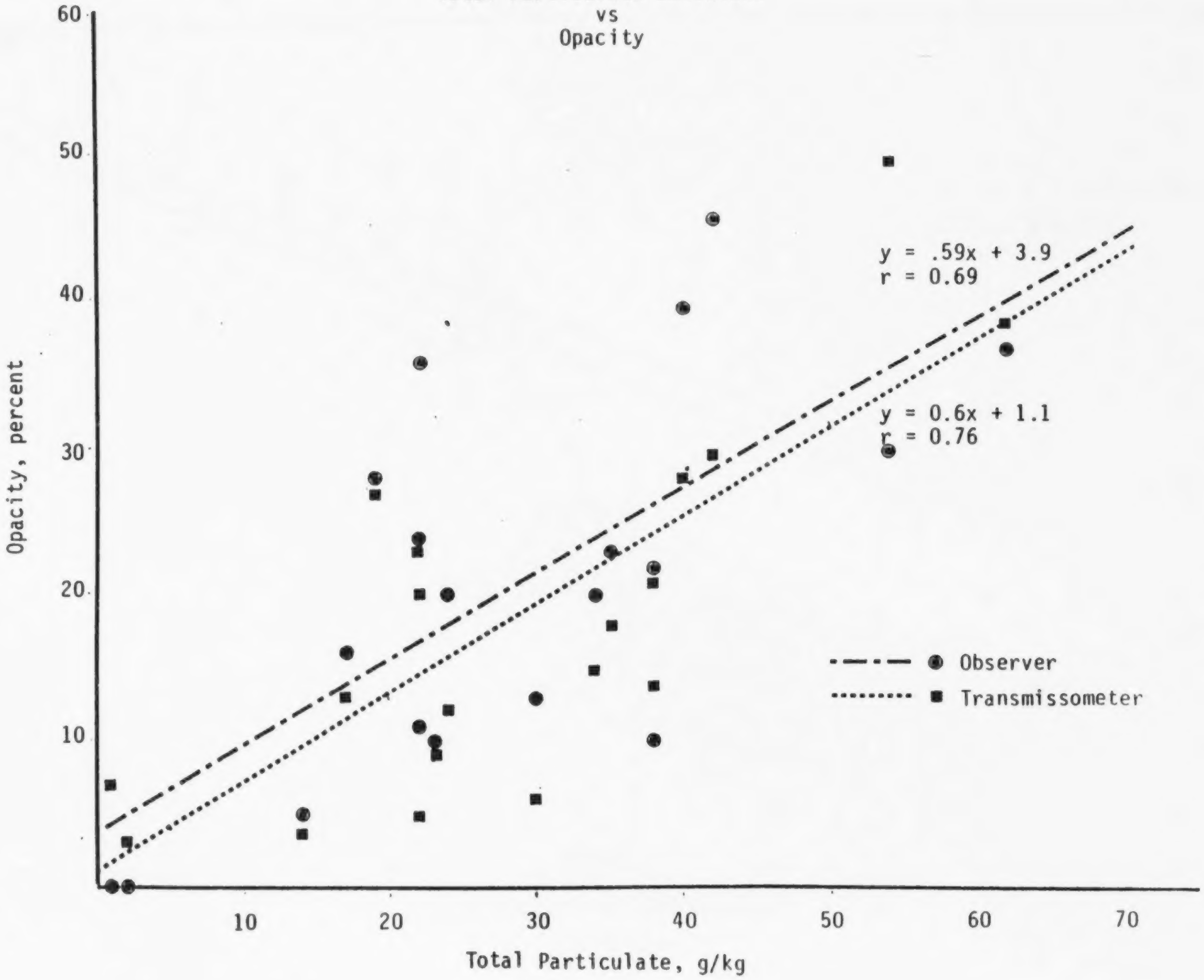


TABLE 46

Summary of Stack Gas Opacity
(Transmissometer and Visual Observer)

Run	Average Opacity, percent	
	Visual Observer[a]	Transmissometer
1	36	26
2	34	50
3	20	15
4	40	28
5	37	39
6	46	29
7	28	28
8	20	12
9	11	5
10	24	20
11	16	13
12	22	21
13	23	18
14	10	14
15	10	10
16	<5	5
17	13	6
18	-0-	7
19	-0-	3

---

[a] Observations not made for all periods of the test run

Smoke Spot Density

Smoke Spot Density measurements were taken at approximately one-half hour intervals during the test runs. An average smoke spot density was calculated for each test run (complete results are reported in the Results Section). Unfortunately, due to a sampling problem, no smoke spots were taken for the ceramic stove (the lowest emission rate).

Figures 92 and 93 present smoke spot density as a function of total particulate concentration and emission rate, respectively. No real correlation is noted for smoke spot density and measured particulate. The majority of the data are clustered around an average smoke spot density of 5 to 7. Basically, it appears the method simply is not sensitive enough to be highly useful. Examination of the test data for individual runs does however, generally show a declining smoke spot value as the test burn progresses. One would expect that concentration is decreasing as the run progresses; consequently, the smoke spot may be useful as an indicator of changes in emissions during monitoring of a particular test burn.

FIGURE 92

Total Particulate Emissions
vs
Smoke Spot Density
(By Test Phase)

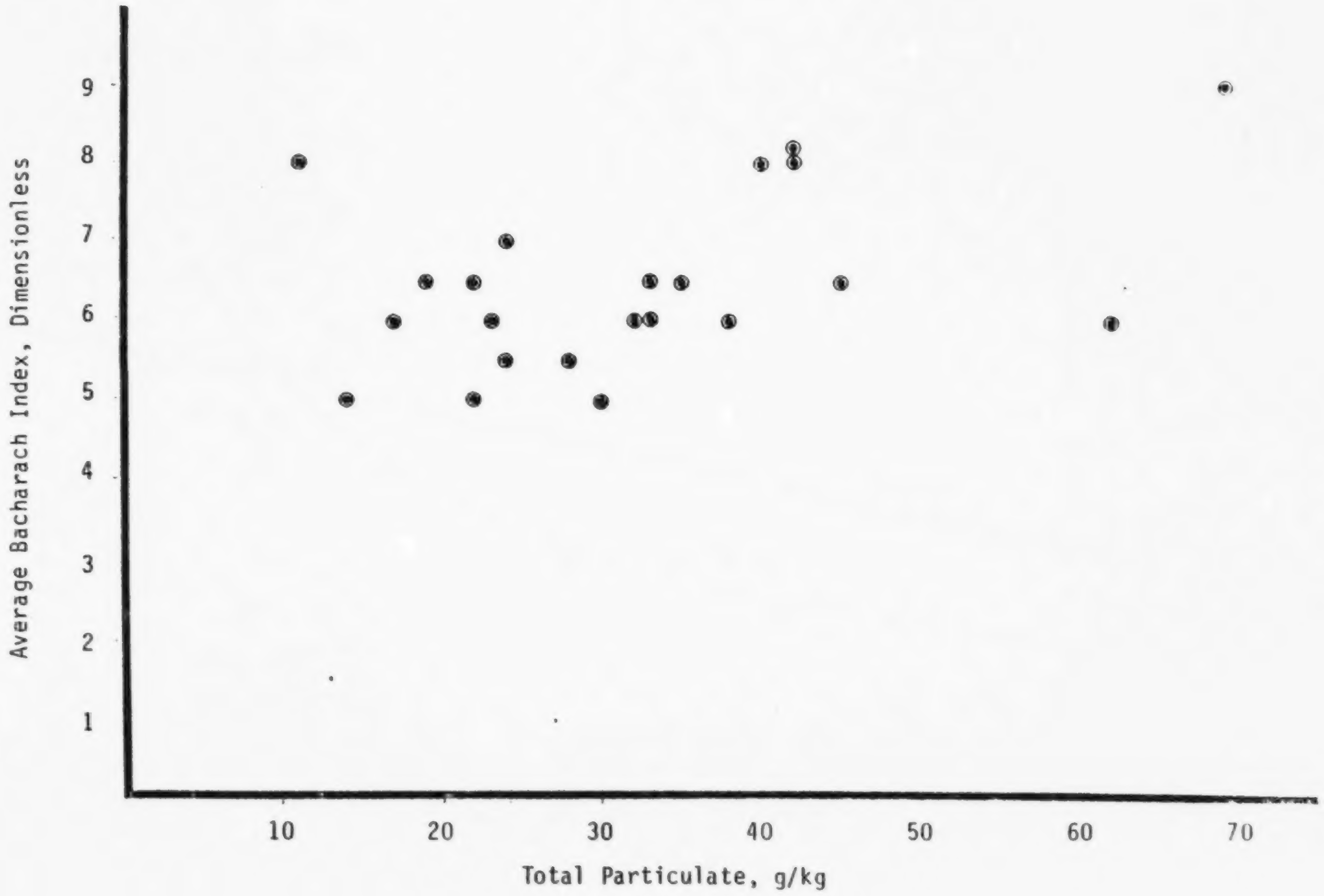
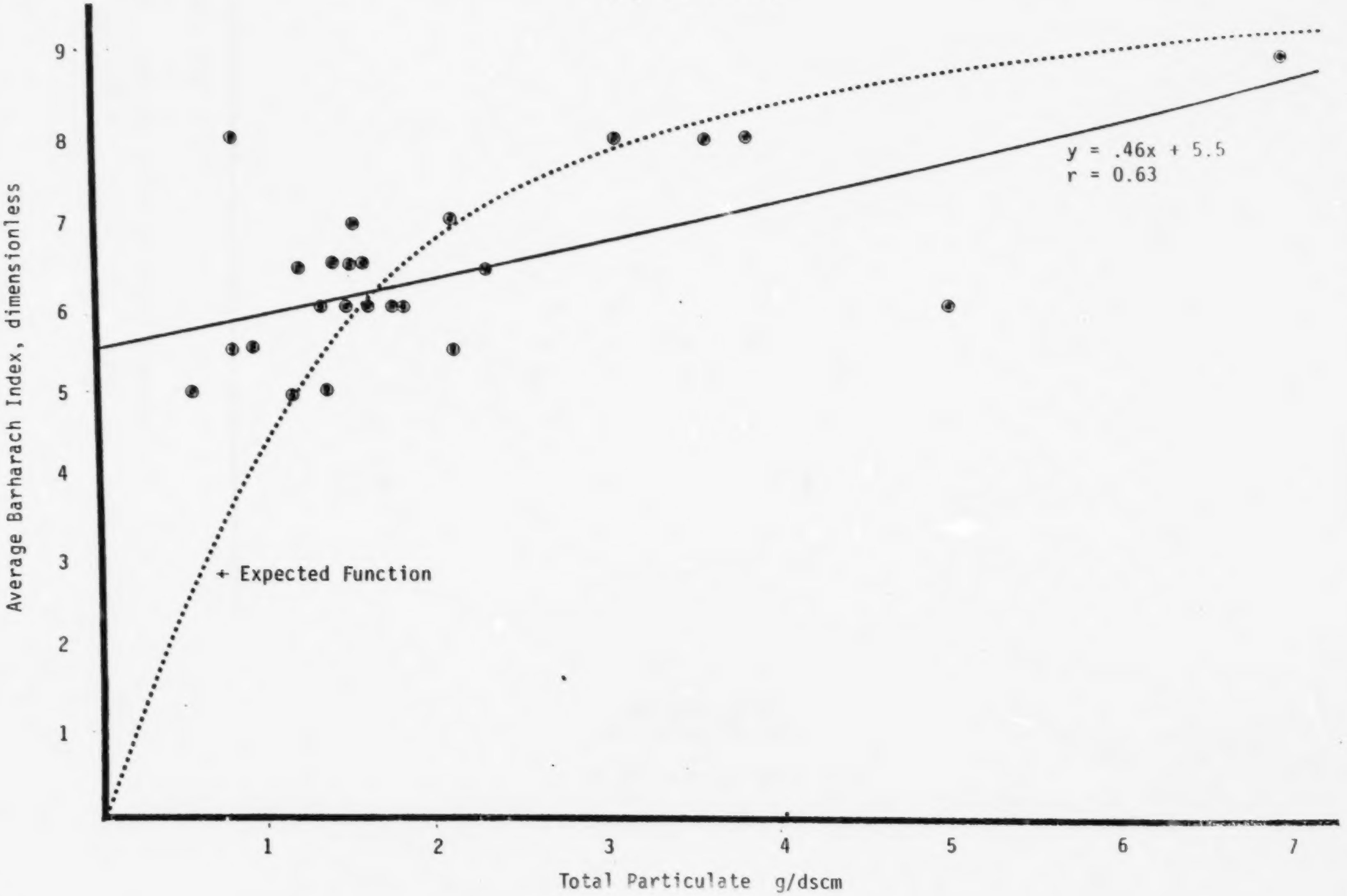


FIGURE 93

Total Particulate Concentration
vs
Smoke Spot Density
(By Test Phase)



Evaluation of Simplified Test Procedures and Discussion of Results Relative to Information in the Literature

Table 47 summarizes average emissions factors for carbon monoxide, gaseous hydrocarbon, and creosote found in the available literature; particulate emission values also are provided. The primary purpose for providing this table is simply to determine if emission rates for the various pollutants fall into the same range. If a correlation exists between particulate and carbon monoxide, for example, then for particulate emissions measured by different researchers within a given range, then carbon monoxide emission rates also should be similar. Of course, "should" is important here, because many variables including stove operation, and measurement methods (not to mention quality assurance) enter into these data collected by the different investigators. Nonetheless, a listing of average ranges seemed useful. For carbon monoxide and gaseous hydrocarbons, average emissions do fall into fairly narrow ranges 45-200 g/kg CO and 7-32 g/kg THC. For creosote a much broader range, 17-11,000 mg/m^2 kg, is found. (Particulate emissions were not measured by any other method for the 11,000 value.) Particulate emissions (filterable) were in the 2-15 g/kg range.

No attempt was made to develop correlation coefficients (such as those prepared for this study) with these data obtained from the literature, or to incorporate any of these data into the correlations prepared in this report.

Some general information relevant to this discussion of simplified test procedures was found in the literature. Cooke, et al[1f] indicates

TABLE 47

Summary of Average Emission Factors for Carbon Monoxide, Gaseous Hydrocarbon, and Creosote (Literature Review)

Investigator	Total Particulate Matter g/kg	Filterable Particulate Matter g/kg	Carbon Monoxide g/kg[A]	Gaseous Hydrocarbon g/kg[B]	Creosote mg/m^2 - kg
DGA/OMNI	27	6 (0.6-14)	115 (20-220)	9[C] (0.4-17)	330 (27-969)
Oregon DEQ[1d]	32	15[D] (0.8-45)	191[E] (42-363)	--	17 (5.7-36.6)
Knight[1j] (Oak)	--	2 (0.2-3.5)	92 (26-185)	28[F] (8.5-78)	--
Knight[1j] (Fir Brands)	--	4 (0.3-8.3)	196 (67-310)	29[F] (11.3-56)	--
Butcher[1k] (1980)	--	4 (1.6-6.4)	100 (63-158)	--	--
Monsanto[11]	10	4	180 (91-370)	--	--
PEDCo[11]	28	--	204	--	--
Battelle[4]	--	--	100 (33-400)	21[F] (2-112)	--
Hubble[12]	--	-- (0.5-22)	-- (55-196)	--	-- (380-3800)[G]
California Air Resource Board[4]	22	13	45 (4-147)	7[H] (.25-16.5)	--
CCRL[4]	--	--	136 (87-184)	32[H] (20-43)	--
Rudling[11]	--	2.6[I] (0.1-10)	90[J] (2-300)	--	--
Shelton[8]	--	--	--	--	6000 (170-11,000)

Footnotes for Table 47

A Method of measurement either orsat or continuous NDIR.

B Method of measurement either Flame Ionization Detection (FID) or Nondispersive infrared analyzer (NDIR).

C NDIR

D Includes data from furnaces.

E Calculated by this author from data in original test reports.

F FID

G Values calculated from reported results as g/kg and collection area of .70 m^2 (3 sections at .57 m length x Π x .13 m diameter)

H GC/FID

I Glass thimble filter.

J Values estimated from graph.

that carbon monoxide and total hydrocarbon emissions "vary" together (no statistical correlation was done); particulate emissions were not measured during this study. Hubble's[1e] data indicates that both carbon monoxide and creosote increase with increasing particulate matter, and similarly Knight's[1j] data indicates that carbon monoxide and total gaseous hydrocarbons follow the trend of the measured particulate emissions. Although neither of these investigators reported a statistical comparison of measurement techniques, Knight does go so far as to recommend an appliance performance rating based on a combined CO/THC/Efficiency measurement.

The most interesting data found in the literature regards creosote measurements. The most significant result was Shelton's[3] data indicating a 75% reduction in creosote deposition from use of a barametric damper. Since the barametric damper can reasonably be expected to have little effect on the emissions actually generated during combustion and emitted to the atmosphere (Shelton did not measure emissions by any means other than by creosote deposition), this implies that creosote deposition can not be expected to correlate well with particulate emissions. The effect of reduced creosote emissions during Shelton's study is likely due to the effect of dilution air and increased stack gas velocity.

Nonetheless, Barnett[7] reports an "excellent correlation" between creosote deposition and particulate emissions measured for five appliances (several runs each). (A correlation coefficient of 0.95 based on average values measured from five appliances was calculated by this author.) A fairly reasonable correlation also was obtained during this study. However, in each case, appliances were operated under very similar conditions for the test runs. Thus. one might conclude that for similar test conditions (e.g., excess air, stack gas temperature) creosote deposition will be a good indicator of emission levels; however, if operating conditions change singificantly, this relationship is likely to fail.

Table 48 summarizes the advantages and disadvantages of the simplified test procedures evaluated during this study. An estimate of costs for each method also is provided. Carbon monoxide and/or hydrocarbon measurements appear to be the best potential candidates for a simplified test method. A correlation coefficient with total particulate emissions of 0.8 for each of these procedures was determined for the data from this study. This correlation was for carbon monoxide concentration (adjusted for excess air) compared to total emissions, g/kg. This is of particular interest because a correlation based on concentration means stack gas volumetric flow rate does not need to be measured; this is a definite advantage for a simplified procedure. Another advantage of this technique is that continuous measurements can be taken and the results obtained instantaneously. This makes the technique especially useful for "screening" stove performance at various operating conditions. Another advantage of the method is that, depending upon the quality of the data required consistent with the purpose of the testing, CO can be measured by several techniques with a wide range of expense. For example, for the crudest screening tests, an orsat could be used to take grab samples; or a portable NDIR unit could be used to make continuous measurements with a reasonable accuracy; finally, for the most accurate measurements,

TABLE 48

Simplified Test Procedures Summarized

Method	Correlation to Total Particulate[a]	Advantages	Disadvantages	Estimated Cost[b]		
				Capital Investment	Per Run	Per Series (9 tests)
Total Particulate	1	• Accurate measurement of emissions including condensibles. • Integrated sample over entire burn cycle.	• Expensive • Long sample time required (1-hr minimum); not ideal for measuring discreet periods within burn. • Experience with method required. -----	\$20,500[c,d]	\$2,100	\$15,000
Filterable Particulate	20-50% of total particulate mass basis. Correlation coefficient not determined	• Accurate measurement of emissions. • Integrates sample over entire burn cycle. • Slightly less expensive than total particulate method.	• Does not measure condensible particulates. • Expensive. • Long sample time required (1-hr minimum); not ideal for measuring discreet periods within burn. • Experience with method required. -----	20,500[c,d]	1,900	12,500
High Volume	--	• Short sample time enables measurement of discreet periods within burn.	• Expensive • Collection efficiency for condensible organics unknown. • Multiple samples required to obtain measurements for entire burn cycle. -----	16,500	1,900	12,600
Carbon monoxide	0.8	• Provides instantaneous and continuous output, excellent for monitoring burn cycle. • Inexpensive to use once capital investment incurred. • Suitable for screening method, using cheaper, less accurate instrumentation • Suitable for field monitoring.	• No direct measurement of particulate.	13,500[e] \$600-2600[f,h]	560 280	4,200 --

TABLE 48 (Cont.)

Method	Correlation to Total Particulate[a]	Advantages	Disadvantages	Estimated Cost[b]		
				Capital Investment	Per Run	Per Series (9 tests)
Total Hydrocarbon	0.8	• Same as Carbon monoxide	• Same as Carbon monoxide	$23,500[e]	$560	$4,200
			• Potential for variable response to different HC species.	$4500-6700[g,h]	280	--
Creosote	0.8 (0.5)	• Uncomplicated to use. • Inexpensive (low level of effort). • No significant capital investment. • Capable of measuring discreet periods within burn cycle.	• Not direct measurement of particulate emitted to atmosphere. • Results likely dependent upon numerous variables such as stack temperature, and excess air.	1,000	250	2,800
Opacity (Transmissometer or visible emission inspector)	0.8	• Inexpensive to use. • Little or no capital investment. • Suitable for field monitoring (visible emission observer).	• Does not directly measure particulate. • Results highly dependent upon excess air levels.	0 - 1,000[h]	280	2,800
Smoke spot density	0.6	• Inexpensive to use. • Low capital investment. • Easy to use. • Very short measurement time; may be used to monitor discreet periods within burn cycle. • Convenient for field monitoring.	• Results dependent upon excess air levels. • Large number of measurements required over entire burn cycle.	75.00[h]	280	2,800

Footnotes for Table 48

[a] Correlation coefficient determined from this study.

[b] See Appendix D for basis of cost estimates.

[c] Includes laboratory quality, CO, CO_2, and O_2 monitors for accurate and continuous determination of stack gas composition for determining stack gas volumetric flow by stoichiometry. Subtract $12,500 for monitors and add $3,000 for orsat and low velocity flow measurement instrumentation equipment (net change - $9,500) if orsat/velocity methods to be used.

[d] Add $5000-10,000 for flame ionization detector if total hydrocarbons analysis is desired.

[e] Delete $1,000 if platform balance not to be used to monitor fuel consumption rate (necessary for emissions as g/kg basis) and results to be reported as concentration adjusted for excess air.

[f] If used as a screening test with orsat or less accurate instrumentation to determine emissions (CO concentration adjusted for excess air).

[g] If used as a screening test with orsat or less accurate instrumentation (e.g., NDIR instead of heated FID) to determine emissions (hydrocarbon concentration adjusted for excess air).

[h] Add $1,000 if platform balance to be used to monitor fuel consumption rate.

a laboratory quality continuous NDIR properly calibrated would be used. Capital investment for a quality laboratory instrument (CO/CO_2) is estimated at about $8,500. A quality FID (heated system) would cost $10,000 (under $5,000 for unheated system).

Creosote deposition has some advantages as a simplified method. For one thing it requires almost no capital investment or significant level of effort to conduct the tests. Furthermore, the method is simple to use; no instrument calibrations or use of gaseous sampling systems is required. An advantage of the method is that it can be used over an extended time period of stove operation (if this is desired to meet the purpose of the evaluation) without any additional effort from the tester. In other words, a sample can be taken for 1-hour, 1-day, or 1-week without any difference in level of effort (excepting stove operation). However, the results of this study indicate a problem with precision (for the coupon technique used) between duplicate samples. Furthermore, Shelton's work casts some doubt regarding the effect variable stove operating conditions has on results.

Opacity correlates well with particulate concentration; however, this really is of little use unless volumetric flow measurements also are taken. The main problem with this technique is the impact excess air has on the opacity. The method has potential as a screening technique with a high probability of type II error (false acceptance), because of the dilution air effect. In other words, if a unit fails an opacity test, one could be reasonably sure that the appliance was not meeting a particular emission level; however, if the unit met a given opacity level, a high uncertainty would exist that the unit actually was meeting the corresponding particulate emission level. Furthermore, as the emissions decrease towards an opacity of zero, it would become increasingly more difficult to measure any further decrease in opacity even with a transmissometer (e.g., below 5 percent opacity it would be very difficult to measure emission changes).

The evaluation of smoke spot density measurements during this study indicated no reasonable correlation with total particulate. No additional data on this method's applicability to small wood burning appliances was found in the literature.

Measurement of filterable particulate emissions (Method 5 front-half) will result in a slightly reduced level of effort; however, the reduced level of effort seems negligible compared to the total level of effort required by either method. Consequently, it would seem logical to proceed with a back-half analysis whenever a Method 5 is conducted. For this reason, no correlation coefficient between total and filterable particulate was calculated for the test data obtained during this study or for data in the literature. However, filterable particulate ranged from 20-60 percent of the total emissions measured for the data reviewed; this is a fairly broad range.

Measurement of filterable emissions by the high volume technique was not evaluated during this study due to budgetary constraints. However, it has been listed in Table 48 as a simplified method because of the interest in this technique. Basically, when one considers that the level of effort required for conducting an emissions evaluation (stove operation, volumetric flow rate measurements, fuel combustion measurements) this method does not result in any significant reduction in level of effort from that required to use EPA Method 5. The major advantage of this method is that a quick sample can be taken and thus discrete emission samples can be taken at various times in the burn cycle. Thus this approach is particularly useful in evaluating changes in emissions during the burn cycle. Of course, depending on the purpose of the evaluation, this can, in fact, be a liability; i.e., when an integrated sample over an entire and long burn period is of interest, it may actually be an inconvenience to have to take multiple samples.

Barnett[7] has conducted numerous tests with his high volume technique to show that his system provides repeatable results if the measurements are taken at a stack gas temperature of less than 250 - 275°F (i.e., at temperatures up to 275°F the amount of material condensing and collecting on the filter is consistent; at sample temperature above 275°F, some material does not sufficiently cool prior to reaching the filter and is not collected resulting in a measured emission level less than that measured when the sample is taken at 275°F). However, no tests have been conducted to determine how these measured emission rates compare with either the filterable or total particulate emission rates measured by the Method 5 sampling system. A comparative test of this nature would be informative.

In summary, the carbon monoxide or hydrocarbon methods appear to offer the greatest advantages and flexibility as simplified procedures. Additional work to verify the correlation with total particulates reported in this study and to determine if the relationship will hold over a variable set of conditions is warranted. Although the correlation of creosote with total particulate emissions is more shakey, additional work in this area to improve the precision of the method and to identify its boundaries would be beneficial since this method is easy to use, requires no knowledge of instrumentation or emissions sampling, and is inexpensive. Finally, a comparative study of the emissions measured with Method 5 and a high volume technique would be extremely useful since such a study would give a basis of comparison for the emissions data already collected by the different methods, as well as define the potential of the high volume method as a "simplified" technique for obtaining emissions data.

REASONABLE EMISSION STANDARDS

One of the objectives of this test program was to evaluate improved technology stoves in order to provide data for defining the level of a reasonable emissions standards. Of interest was an achievable emission level when operating appliances at a moderate to low burn rate (less than 2.5 kg/hr).

Of the three improved technology stoves and two retrofit devices tested, only one stove resulted in emissions significantly below the norm. This appliance (ceramic stove) also was operated at a higher burn rate than the desired rate, which undoubtedly is expected to result in lower emissions. Nonetheless, this emission rate can serve as an indication of an emission rate which may be achievable for appliances operating at lower fuel combustion rates. None of the other stoves tested in this program came close to meeting the emission rate of the ceramic stove. In fact, only one of two tests for the catalyst-modified combustion stove even resulted in a measurably lower emission rate than the airtight box stove.

Table 49 summarizes the levels obtained for the various emission parameters measured for Run 19 with the ceramic appliance and Run 16 with the catalytic-modified combustion appliance. Run 19 was the higher emitting test of the two test runs for the ceramic stove, but also had a burn rate which was considerably lower than Run 18. The two runs for these two stoves can serve to illustrate the range for a reasonable emission standard.

It is very important to mention that any meaningful emission standard

TABLE 49

Emission Standard Range

	Run 16 Catalytic Modified Combustion	Run 19 Ceramic Appliance
Total particulate, g/kg	14	2
Front-half particulate, g/kg	3.5	1
Creosote, mg/m^2 kg	90	27
Carbon monoxide, g/kg	80	50
Hydrocarbon, g/kg	4	1
Adjusted[a] ppm	230	40
Opacity, average percent	5	0
Parameters during these tests:		
Burn rate[b], kg/hr	3.0	3.9
Fuel load to combustion rate ratio[c], kg/Btu/hr x 10^4	1.3	1.1
Fuel load to stove volume ratio[c], kg/m^3	100	99

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[a] Adjusted for dilution air

[b] Dry basis

[c] Wet basis

The results of this emission test program were disappointing in terms of providing emission data which justifies an emission standard below the normal level of a well-operated typical stove (15-20 g/kg total particulate). Nonetheless, the emissions obtained from the ceramic stove point towards a reduced emission level which should be achievable.

Discussion of Results Relative to Information in the Literature

Numerous test programs have been conducted on various residential wood combustion appliances during the past several years. The purpose of these various test programs has ranged from evaluating emission characteristics from innovative and or different stove designs (e.g., Oregon DEQ[1d], Barnett[1a]) to determining an emission factor from typical home-operated units (e.g., Sandborn[1h]). Since it has been shown that appliance emission factors can be affected by a number of variables, results obtained from different studies must be evaluated and compared with extreme caution, if at all. Factors which may affect emission rates include, but are not limited to: emission measurement method, stove operating technique (fuel combustion rate, fuel charge size, whether or not start-up and burn down are included in test), fuel characteristics (type, size, moisture content), and type of appliance.

Nonetheless, in attempting to define what constitutes a reasonable emission level, it is certainly necessary to discuss the results obtained by other investigators and reported in the literature. The purpose of this review is 1) to provide a basis by which to compare the results obtained during this study, 2) to identify data obtained by other investigators is heavily dependent upon stove operating conditions. Consequently, established emission rates are somewhat meaningless unless stove operating conditions also are established. The results in Table 49 should be reviewed keeping this in mind. This point is exemplified by the results obtained with the catalyst-modified combustion stove. As already noted, significantly higher results were obtained during the second test run for the catalyst-modified combustion stove. This can reasonably be explained by the operating parameters during the test run. In an attempt to reduce the burn rate (2.1 kg/hr vs 3.0 kg/hr) stove combustion chamber temperatures were below the level necessary for proper catalyst operation. A similar result was obtained during testing of the catalytic box stove; a change in burn rate from 1.7 kg/hr to 2.2 kg/hr resulted in a reduction of emissions from 38 to 23 kg/hr.

The number of tests on the improved technology appliances in this program is very limited and in the authors opinion is not adequate to clearly characterize the emission levels which might be obtained from the appliances. In order to accurately access the emission characteristics of these stoves, a complete series of multiple emission tests at different fuel combustion rates would be required. Whether or not any of these appliances warrant further testing is another question. It is the author's opinion that the ceramic stove should be operated under conditions to determine the actual instantaneous heat output of the unit. Such testing would enable one to determine if the stove does in fact have adequate heat storage properties permitting it to produce an even heat output while being operated in a batch type mode.

which might be particularly useful in helping to define a reasonable emission level, and 3) to identify data which would suggest particular appliances that potentially have low emissions and warrant further investigation. Consequently, although the majority of the RWC particulate emission data known to be available is tabulated herein, the discussion of the data is not intended to be all encompassing (e.g., no attempt is made to discuss such factors as affect on emissions of fuel size, fuel type, etc.). Readers are urged to refer to the original publications prepared by the investigators for further information and insight.

Table 50 summarizes the emission rates obtained by various investigators and is useful in providing a general idea of typical emission levels. As average emission levels, even for each investigator, the data may inherently encompass a wide range of stove types, operating parameters, etc. (such as in this study). A cursory examination of these data indicates that an emission rate of greater than 20 g/kg total particulate and 5-10 g/kg filterable particulate is typical.

Table 51 presents the same data in a format which provides more detail. The data are presented first by stove type (design category), with each investigators data listed separately. Ranges also are presented along with the average values. The particulate emission rates in this table are 1) total particulate -- this generally includes both the filter catch and analyses of "back-half condensibles" by EPA Method 5. In some cases (e.g., Oregon DEQ[1d] and this study) an extra unheated filter was included as part of the back-half to catch any material leaving the condensor train.

TABLE 50

Summary of Average Emission Rates

Investigator	Burn Rate kg/hr[a]	M/Q kg/10^4 Btu-hr	Particulate			Carbon Monoxide g/kg[a]	Comments
			Total g/kg[a]	Hi Vol g/kg[a]	Filterable g/kg[a]		
Del Green/OMNI	2.5	2.3	27	--	6	115	
Del Green/OMNI (Excluding fuel moisture tests)	2.5	2.0	19	--	4	115	
Oregon DEQ[1d]	3.1	4.9	32	--	15	--	g
Sanborn[1h]	2.4	1.5	27	--	18	--	b,c
Barnett[1a,7]	1.5	2.3	--	7	--	--	b,d
Knight[1j]							
(Oak)	5	--	--	--	2	92	e
(Fir Brands)	7	--	--	--	4	196	e
Butcher[10] (1979)	2.1	0.8	--	9	--	--	
Butcher[1k] (1980)	2.4	0.8	--	3.5	--	100	
Monsanto [11]	7.2	--	10	--	4	180	f
Furnaces:							
Oregon DEQ[1d]	9.3	2.4	9	--	2.6	--	
Sanborn[1h]	5.7	1.4	12	--	5.5	--	b,e

Footnotes for Table 50

[a] Dry basis.

[b] M/Q estimated values,9000 Btu/lb, dry basis fuel, 15 lb fuel charge assumed for Butcher's work.

[c] Investigator reported values on wet basis fuel; factor of 0.8 (20% moisture fuel) used to adjust values.

[d] Average value (unweighted for number of runs) for 14 different appliances; some tests conducted with modifications to appliances; investigator reported results on wet basis, factor of .70 (30% moisture fuel) used to adjust values.

[e] Tests operated at three distinct burn rages: low, medium, and high; load size adjusted for each burn rate (e.g., less wood loaded for low burn rate) presumably resulting in fairly constant M/Q (actual load sizes not provided with data).

[f] Includes results from tests with both seasoned and green fuels.

[g] All tests conducted from cold start(i.e., no hot ash bed and a cold stove).

TABLE 51

Particulate Emission Data Summary
(Literature Review)

Stove Type	Investigator	Burn Rate kg/hr[a]	Wood Type[b]	Test Method[c]	Number of burns	Emissions, g/kg[a]			Comments
						Total[d]	Filterable[e]	Hi Vol[f]	
Ceramic	DGA/OMNI	5.2 (3.9-6.4)	DF	5/BH	2	1.5 (1-2)	0.8 (0.6-1.0)		
Catalytic	DGA/OMNI	2.0 (1.7-2.2)	DF	5/BH	2	31 (23-38)	5 (4.8-5.9)		
	Oregon DEQ[1d]	2.2 (1.8-2.6)	DF	5/BH	2	25 (21-30)	6 (4.7-6.6)		p
	Barnett[7]	1.4	RO/SM	HV	1			7.0	
	Barnett[7]	1.4 (0.8-2.0)	RO/SM	HV	3			1.0	
	Corning[1b]	NA	NA	C	NA	85-95%			g
Catalytic/Modified Combustion	DGA/OMNI	2.5 (2.1-3.0)	DF	5/BH	2	22 (14-30)	5 (3.5-5.7)		
Airtight Box	Sanborn[1h]	3.2 (2.6-3.8)	MHW	5/BH	2	14 (13-15)	6 (4.5-7.0)		h
	Barnett[1a]	1.7 (0.8-2.4)	RO/SM	HV	6			7.2 (2.6-16.9)	i
	Butcher[10]	2.1 (0.9-4.0)	O/P	HV	26			9.3 (1.3-24)	
	Butcher[1k]	2.4 (1.7-3.4)	O/H	HV	10			3.5 (1.6-6.4)	
Modified Box	Barnett[1a]	1.6 (1.1-1.9)	RO/SM	HV	9			9.1 (3.5-14.5)	i

TABLE 51 (Cont.)

Stove Type	Investigator	Burn Rate kg/hr[a]	Wood Type[b]	Test Method[c]	Number of burns	Emissions, g/kg			Comments
						Total[d]	Filterable[e]	Hi Vol[f]	
Step	DGA/OMNI	2.3 (1.7-2.9)	DF	5/BH	6	36 (19-62)	9 (5-16)		
	DGA/OMNI	2.4 (1.9-2.9)	DF	5/BH	2	21 (19-22)	5 (4-6)		j
	Oregon DEQ[1d]	2.6 (1.5-3.6)	DF	5/BH	4	43 (23-74)	25 (13-43)		p
	Barnett[1a]	1.7	MHW	HV	1			7.2	i
	Sanborn[1h]	2.7 (2.2-3.6)	MHW	5/BH	3	38 (24-53)	21 (14.0-28.1)		
	Monsanto[11]	7.4 (6.6-7.8)	O/P	5/BH	4	10 (4.1-19)	3 (1.8-6.3)		k
	PEDCo[11]	6.2	P	5/BH	1	28.3	21		
Modified Step	Barnett[1a]	1.6 (1.2-2.0)	RO/SM	HV	4		6.4 (3.0-12.1)		i
Baffled	Barnett[1a]	1.5 (0.9-2.0)	RO/SM	HV	3		7.7 (5.7-11.4)		i
	Sanborn[1h]	2.1 (1.4-2.6)	MHW	5/BH	6	26 (13 - 44)	18.9 (8.3-22.4)		h
	Hubble[1e]	NA (.8-7.7)	O	CI	NA		NA (0.5-22)		l
	Monsanto[11]	7 (6.0-8.4)	O/P	5/BH	4	10 (6-19)	4 (2.5-7)		k

TABLE 51 (Cont.)

Stove Type	Investigator	Burn Rate kg/hr[a]	Wood Type[b]	Test Method[c]	Number of burns	Emissions, g/kg			Comments
						Total[d]	Filterable[e]	Hi Vol[f]	
Cross Draft	Barnett[1a]	1.4 (1.0-2.2)	RO/SM	HV	6			4.5 (1.5-6.7)	i
Down Draft	Barnett[1a]	2.0	RO/SM	HV	1			5.2	i
Convective	Barnett[1a]	1.3 (1.0-2.3)	RO/SM	HV	26			14.4 (4.1-36)	i
	Sanborn[1h]	1.6	MHW	5/BH	1	26	16		h
Modified Convective	Barnett[1a]	1.3 (0.7-2.0)	RO/SM	HV	5			10.0 (2.9-17.6)	i
Gasifier	Oregon DEQ[1d]	4.5 (4.5-4.5)	DF	5/BH	2	26 (20-31)	8 (5.1-10.9)		p
Unidentified/Misc.	Knight[1j]	5 (2-9)	O	5	15		1.5 (0.23-3.5)		m
	Knight[1j]	7 (2-13)	FB	5	9		4.4 (0.3-8.4)		m

TABLE 51 (Cont.)

Stove Type	Investigator	Burn Rate kg/hr[a]	Wood Type[b]	Test Method[c]	Number of burns	Emissions, g/kg			Comments
						Total[d]	Filterable[e]	Hi Vol[f]	
RETROFITS:									
Non-catalytic	DGA/OMNI	2.3 (2.2-2.4)	DF	5/BH	2	37 (35-38)	7 (6.1-7.4)		
	Oregon DEQ[1d]	4.2	DF	5/BH	1	10	2.6		p
	Shelton[2,3]	NA	HW/SW	--	NA	(23-41)			n
Catalytic	DGA/OMNI	2.4 (2.1-2.6)	DF	5/BH	2	20 (17-22)	3.5 (3.3-3.7)		
	Shelton[2,3]	NA	HW/SW	--	NA	(45-51)			n
FURNACES:	Oregon DEQ[1d]	9.3 (4.7-16.4)	DF	5/BH	4	9 (3-19)	2.6 (0.8-4.2)		p
	Sanborn[1h]	5.6 (3.6-8.2)	DF	5/BH	3	12 (8-18)	5.5 (4.1-6.9)		h

Footnotes for Table 51

a. Dry basis

b. DF - Douglas fir; MHW - mixed hardwood; O - Oak; FB - fir brands; RO/SM - Red oak/Sugar Maple; P - Pine; H - Hemlock, HW - unspecified hardwood, SW - unspecified softwood

c. 5/BH - EPA Method 5 with back-half gravimetric analysis;
5 - EPA Method 5, front-half only; HV - high volume with dilution;
CI - Cascade Impactor, with filter at stack temperature;
C - Condensate trap

d. Heated filter catch

e. Filter catch and condensible fraction

f. Unheated filter catch with high volume sampler

g. Percent reduction across catalyst

h. Investigator reported values on wet basis fuel; factor of 0.8 (20% moisture fuel) used to adjust values

i. Investigator reported results on wet basis; factor of 0.7 (30% moisture fuel) used to adjust values

j. Does not include fuel moisture test runs

k. Includes results from tests with both green and seasoned fuels

l. Tests conducted at steady state conditions (i.e., does not include start-up/burn down)

m. Tests conducted at three distinct burn rates (low, medium, high); load size adjusted for each burn rate (i.e., less wood used for low burn rate, etc.)

n. Percent reduction in creosote deposition in flue

p. All tests conducted from cold start (i.e., no hot ash bed and with cold stove)

NA - Not available

2) Filterable particulate -- this generally constitutes the front-half heated filter catch for EPA Method 5 and 3) High volume particulate -- this constitutes filterable particulate collected on the unheated filter of a "high-volume" (high air sampling rate relative to Method 5) sampling unit. Typically with this method, ambient dilution air is added to the sample prior to its contact with the filter. The proponents of this method generally believe that the emissions collected by this technique is nearly equivalent to the total particulate emissions measured by Method 5 and/or that this technique of measurement more adequately represents the "particulate" emissions which would be measured in the ambient atmosphere (e.g., by an ambient monitor). Because of the uncertainty as to whether high volume data is more nearly equivalent to total or filterable particulate (as defined above), these data have been listed separately by this author. The conservative approach is to assume high volume emission data underestimates total particulate emissions and more closely approximates the results which would be expected from the filterable fraction; this is the approach taken here when discussing and evaluating the test data.

It has already been shown in this study and by other investigators[1d,1k,10] that emissions vary inversely with burn rate; consequently, higher emissions are expected at lower burn rates. In this study, a burn rate of 2.5 kg/hr was assumed to be typical of a moderate to low burn rate which might typically be used in the Pacific Northwest. Barnett[1a,7] has done extensive studies in New York State and has generally determined that burn rates were in the range of 0.8 - 2.8 kg/hr, with a burn rate of 1.6 kg/hr being "typical".

Emission tests conducted at burn rates much greater than 3.0 kg/hr are probably of little value in establishing meaningful emissions data for RWC appliances. Note that use of the burn rate (kg/hr) parameter is actually a simplication; since large appliances are intended for higher heat outputs and will require higher burn rates. Consequently, a "high" burn rate is appropriate for large units intended to provide high heat output. However, the point is that most homes do not have a high heat demand from the appliance. Therefore, the appliances would be operated at low burn rates. The factor M/Q (kg wood charged/10^4 Btu/hr) is valuable in establishing a norm in this respect, since larger appliances will hold a larger charge and are intended to be operated at a higher burn rate. Nonetheless, for this discussion, it is assumed that evaluation of emissions at burn rates less than 3.0 kg/hr is desirable.

The results obtained in this study have already been discussed in detail; with the exception of the ceramic stove, no significant emission reductions from the norm were obtained from the improved technology appliances tested. The Oregon Department of Environmental Quality[1d] was involved with emissions testing conducted by two consulting firms (OMNI Environmental,and Seton, Johnson and Odell) with the purpose of evaluating improved technology appliances. The results of these two test programs also yielded little in the way of a measurable emissions reduction from these devices. The appliances tested included a catalytic box stove, gasifier stove, non-catalytic control retrofit, and two furnaces, in addition to a standard step stove. An average total particulate emission rate of 32 g/kg was obtained during this test program. Only the furnace and the non-catalytic add-on device yielded emission reductions. The furnaces had an average emission rate of 9 g/kg with one furnace operating at 3.6 g/kg. However, both furnaces were operated at a high burn rate. Although the burn rate was high, the fuel load to combustion rate ratio (M/Q kg fueled/10^4 Btu/hr) was not particularly low (2.4); in other words, these units were built to provide a large heat output. The significance of these results are that like the ceramic stove, a low emission rate (less than 5 g/kg) is achievable when efficient combustion is attained.

The one test run for DEQ with the non-catalytic add-on device (same device as tested in this program) did indicate a reduction of 50% in emissions from the airtight stove operated at similar conditions (10 vs 20 g/kg). About 80% of the reduction was achieved in the filterable portion and 30% in the condensible which would be expected, since this device basically consists of a filtering medium. As previously indicated, during this study, no emission reduction was noted for two tests conducted with this device. Shelton[2,3] recently conducted tests with this device (and two other retrofit devices) to determine if these devices were useful in reducing creosote deposition in the flue pipe. Shelton found that this device reduced creosote emissions by 21% to 45% (21% when liquid creosote collecting in the flue pipe tee was considered). Shelton's test were conducted by operating eight stoves simultaneously under identical conditions with one pair of stoves fitted with each of the three devices to be tested and one pair of stoves with no device to serve as the control. The stoves were operated for a period of ten days under different operating modes (low to high burn) and with different fuels. The creosote deposition at the end of the test period was gravimetrically determined. The other two retrofit devices tested by Shelton were a catalytic retrofit (same unit as tested in this emission test program) and a barometric damper. Reductions in creosote deposition of up to 45-50% were obtained by Shelton during his study with the catalytic unit. The best performance (i.e., greatest reduction) was obtained under low fire conditions. Under low fire conditions a temperature rise of 450 to 615°F across the catalyst was typical; at high fire a rise of 350 to 450°F was noted. This performance is significantly better than the results obtained during this emission study -- 125 to 300°F temperature rise across the catalyst with no measurable reduction in emissions when compared to the two runs conducted without the device under similar conditions (burn rate and fuel moisture content). These results reinforce the belief that proper catalytic action is critically dependent upon several factors including flue gas temperature, oxygen availability, residence time at the catalyst, and the proper mixing of gases and combustion air. Nonetheless, Shelton's results indicate reduction of emission levels by catalytic action can be achieved under some operating conditions. To what degree the conditions necessary for emissions reduction by catalytic action is dependent upon appliance design, appliance operating conditions and/or operator actions is unclear at this point. Proper catalytic action is no doubt a function of all three of the above; the limiting factors have yet to be clearly defined. The third device tested by Shelton, the barometric damper, resulted in the most significant creosote reduction -- 75%. This is a significant finding since this indicates creosote deposition is not necessarily a good measure of particulate emissions to the atmosphere. There is no reason to expect such a significant reduction in emissions to the atmosphere from use of a barometric damper (some reduction might be obtained due to more steady burn conditions). Therefore, the conclusion is that creosote deposition was significantly reduced due to such factors as dilution of the stack gas effluent and increased stack gas velocity (i.e., decreased residence time); however, emissions to the atmosphere were probably not significantly reduced. This raises some question as to the correlation between creosote reduction and actual reduction of emissions to the atmosphere achieved by the other two devices. It is quite possible that due to other factors (e.g., stack gas dilution from secondary air required for the catalytic unit) the creosote reductions measured for the other two devices are, in fact higher than the actual emissions reductions achieved.

Barnett[7] also tested two catalytic appliances. One appliance yielded no significant emission reduction while the second appliance significantly reduced emissions. Barnett has tested a number of appliances (with and without modifications such as secondary air, added fire brick, added baffles, and thermostatic control) in order to evaluate performance of the different appliance design types. Appliance types evaluted include thin wall, box, step, cross draft, down draft, and catalytic; all of Barnett's tests were conducted at a low to medium-low burn rate (0.8 - 2.2 kg/hr) with the majority of the tests conducted at about 1.6 kg/hr; this is the combustion rate at which Barnett achieves a stove surface temperature of approximately 300°F. Barnett does use a high volume sampling technique so that the numerical emission values he has obtained can not directly be related to the data obtained by the total EPA Method 5 train (this author's opinion). However, taking the conservative approach, Barnett's results can be considered equivalent to the filterable portion of the Method 5 sample. This is relatively unimportant since the trend in Barnett's results are of interest here. For the majority of Barnett's tests, an average emission rate of 7 g/kg[a] was measured. Emissions from the thin walled stove (without modifications) at 14 g/kg were considerably higher than this mean value. No significant reduction in emissions was noted for the catalytic box stove (same appliance as that tested by Oregon DEQ[1d]). As with most devices tested by Barnett and other investigators, the catalytic box stove exhibited a significant increase in emissions with a corresponding decrease in burn rate. However, the second catalytic appliance recently tested by Barnett (catalytic appliance of Barnett's own design) exhibited a significant (85%) reduction in measured emissions (1 vs 7 g/kg). Furthermore, this emission rate did not vary tremendously over the range of burn rates tested (approximately 0.8 - 2.2 g/kg). This emission rate of 1 g/kg measured by this high volume method would (taking the conservative approach) be equivalent to 2-5 g/kg total particulate by EPA Method 5 with back-half analysis.

Sanborn[1h] conducted a series of tests on appliances actually installed in homes with the purpose of estimating an emission factor from wood stoves.

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[a] Note that Barnett's results were reported on a wet basis; the results and burn rates have been adjusted to dry basis using a factor of 0.7 (30% moisture fuel).

The average emission rate measured by Sanborn, 27 g/kg total particulate, is very similar to the average rates measured by the Oregon DEQ, 32 g/kg, and measured during this study, 27 g/kg (19 g/kg without fuel moisture tests). Sanborn's data provides little valuable information, however, in regards to evaluating improved technology appliances. It is worth mentioning that two furnaces were tested and an average emission rate of 12 g/kg was obtained with the units operating at about 5.6 kg/hr combustion rate (2.4 kg/hr overall combustion rate for Sanborn's study). These results compare well with the Oregon DEQ's results for furnaces 9 g/kg at a burn rate of 9.3 kg/hr (one furnace was measured at 14 g/kg and the other at 4 g/kg during the DEQ tests).

The emission tests summarized in Tables 50 and 51 by the other investigators (Knight, Monsanto, PEDCo, and Butcher) are not discussed in further detail, because they do not generally include results useful for evaluating emissions from improved technology appliances and/or because the tests were conducted at higher burn rates (5-7 kg/hr range).

Several relatively new appliances which have not been emission tested offer the potential to reduce emissions; several of these units are briefly mentioned here. These happen to be appliances of which the author is familiar and there is likely to be other improved technology units currently available on the market with which the author is not familiar. Lack of mention of any particular appliance is no direct reflection on the worthiness of a particular appliance, as a potential candidate for low emissions.

Cooke and Allen[1f,13] characterized the effect on emissions of various combustion modification techniques. This evaluation was conducted by measuring changes in carbon monoxide and total gaseous hydrocarbon emissions, as well as various combustion parameters (e.g., temperatures). One of the modifications identified as resulting in reductions was secondary combustion; however, they noted that it was extremely difficult to attain and maintain the conditions (temperature and air) needed to sustain secondary combustion. Nonetheless, several appliances have recently entered the market which purport to utilize the principle of secondary combustion to increase efficiency (and consequently, reduce emissions). Three of these units are unique in that they utilize baffle plates with air jets to direct the gases emitted to a secondary chamber for combustion before exiting the appliance. One of these units, the Brugger Ugly Duckling (from New Zealand) was considered for testing in this study, but due to financial limitations, could not be included. A second unit manufactured in New Zealand, the Kent Stove, also uses this secondary combustion approach. Limited test data is available on this unit (provided by distributor) which indicates a filterable emission rate in the 1-5 g/kg range with the unit operating in the 2-3 kg/hr combustion rate range. Actual test conditions and methods used were not clear at the time of preparation of this report.

The new Jøtul Model 201 also uses this basic technique. Emissions tests have not been conducted on this unit; however, Jøtul reports[5] efficiencies of 75-78% for the unit while operating at burn rates in the 0.8 - 2.0 kg/hr range. A large number of catalytic appliances have entered the market; a recent issue of Wood'n Energy Journal[14] lists 23 different catalytic units that are commercially available; the emissions reduction potential of these units is unknown.

In summary, the results of this study indicated only one unit tested -- the ceramic stove -- resulted in a significant reduction. However, due to the high burn rate of this unit, the meaningfulness of the low emission rate obtained (2 g/kg) is somewhat obscured. Further testing of this unit's heat output characteristics is warranted. However, the low emission rate obtained from this unit, as well as from one furnace tested by the Oregon DEQ suggests that an emission level of 5 g/kg (1 g/kg filterable) is achievable but not necessarily at the low burn rates typically used in small home appliances. Test data[7] from the literature reviewed indicates one catalytic unit has been able to achieve an 85% emission reduction from the emission levels obtained by typical appliances when operated at low burn rates; this percentage reduction results in an emission factor of 1-5 g/kg total particulate (depending on how one interprets the results from the high volume emissions testing method).

Based on the data obtained during this study and on the literature reviewed, an emission level of from 15-20 g/kg total particulate (5-10 g/kg filterable) is reasonable to expect from well operated and designed commercial units currently available. To suggest an emission level of 5 g/kg total particulate (1 g/kg filterable) for small home appliances operated at low burn rates is "technology forcing" at this point in time; limited data are available to indicate that one or two units meet this level, and that larger units operated at high burn rates meet this level.

Although no significant emissions reduction was noted for the retrofit devices (catalytic and non-catalytic) during this study, Shelton's[2,3] results indicate a reduction of from 20-50% (based on creosote deposition).

This emission reduction would not result in an emission rate near the level expected to be achievable from improved technology stoves as discussed above (5 g/kg total particulate), but would likely result in average emissions in the 15-20 g/kg range from existing units. Nonetheless, in any event, any emission reduction of 20-50% for existing units is significant.

The potential effect of emission test methods and stove operation on emissions already has been discussed. Consequently, it should be understood that in defining any emissions level certain parameters regarding these two variables must be established. For this discussion the author has basically assumed the appliance is operated at a burn rate of less than 3 kg/hr and that emissions are measured by EPA Method 5 with back-half analysis. For any emissions measurement program to determine and/or compare emissions from various appliances (whether for certification or research purposes), stove operating procedures and test methods should be carefully defined (particularly stove operating procedures) if the results are to be meaningful. Development of such a standard test protocol is well outside the scope of this project.

One final note regarding emissions levels is in order. The entire discussion has revolved around total or filterable "particulate matter" and innovative technology to reduce these emissions. No mention has been made of Polycylic Organic Matter (POM) emissions. Since these emissions are known to be hazardous, attention also should be given to determining the level of POM emissions from appliances. Unfortunately, methods for determining POM emission levels tend to be expensive. Nonetheless, certainly on a research basis, more information regarding POM emission levels should be obtained.

QUALITY ASSURANCE

The quality assurance program for Task 5 focused on instrument calibration, adherence to standard test procedures, and calculations review. Key aspects of the quality assurance program followed are discussed below. Supporting data for instrument calibrations, etc. are presented in Appendix C.

QUALITY ASSURANCE RECORDS

As required by the contractual agreement a quality assurance log book was maintained by the Task Manager for recording general information such as records of meetings, telephone conversations, etc..

In addition, two separate log books were maintained at the test site. The Laboratory Book was maintained for the purpose of recording the wood moisture measurement information. The Test Log Record was maintained as a general log book for recording any information pertinent to operation of the appliances and to performance of the emissions tests, both during pretest trial burns and during the emissions tests. These log books (three) are to be submitted to EPA as part of the file for this project.

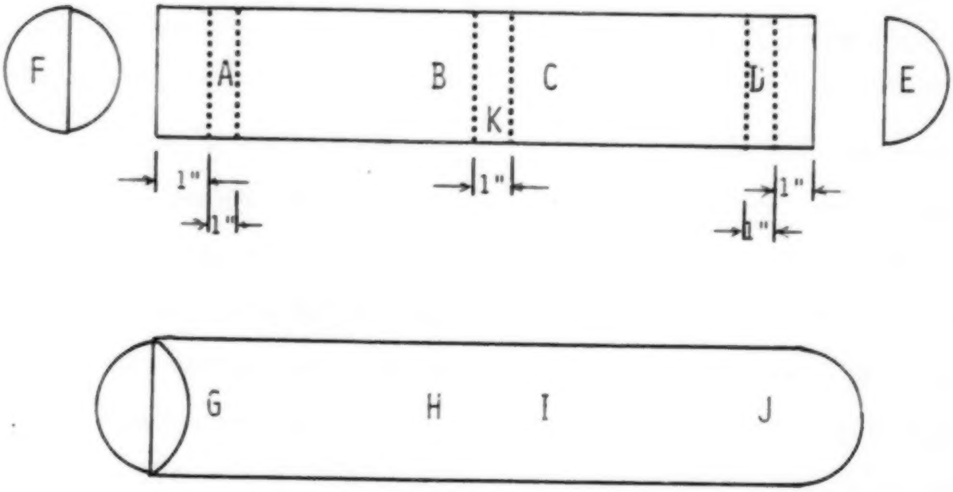
WOOD MOISTURE DETERMINATION

Wood moisture was measured by a Delmhorst moisture meter. Prior to beginning the emission testing, the results obtained by this technique for six different pieces of fuel were compared to the moisture content obtained by measuring weight loss of the wood when heated to 105 C. All tests were performed on logs split into halves. A total of 22 readings were taken for each log at 11 different positions. At each position a reading was made at 1/2" and 1" depths. Four positions on the split face were tested in an evenly spaced traverse, beginning and ending 1" from the ends; the same was done for the bark side of the long. Additional readings were taken at each end and at a point on the split face midway between the ends and 1/2" from the edge. Immediately after the moisture readings were made, 3 one-inch thick sections were cut. One section was cut from the center and one each cut from a point 1 1/2" from each end respectively. Each section was sealed in a plastic bag and sent to a laboratory for analysis by the ASTM Oven Drying Method. Figure 94 indicates the locations of the moisture meter measurements (A - K) and the cross-section cuts (A, B, C, and D). Three logs were tested on 6/30/81 and then three more logs were tested on 7/07/81 to confirm results. Based on the results of these tests, a standard measurement procedure for the emission tests was decided upon.

The best correlation of the moisture meter with the results from the Laboratory Oven Method was an average of readings A-D and G-J at a 1/2" depth. For each log the values were within ±2%, except for one sample which was ±3%. The average for all six logs, readings A-D and G-J was

FIGURE 94

Wood Moisture Measurement


F
A
B
C
D
E
K
1"
1"
1"
1"
1"
G
H
I
J

25.5% moisture, while the average oven method for all six logs was 25.8% moisture.

The 1/2" depth readings give a better correlation since they detect the high moisture content just beneath the bark. The end readings (E & F) were consistently lower than the average. The edge reading (K) is unnecessary. Measurements at these eight points was used for the duration of the tests. The results for the fuel moisture quality assurance tests are reported in Appendix C. Additional quality assurance checks were conducted on 7/27/81, 8/07/81, 8/31/81, and 9/15/81.

Moisture meter readings for the high moisture fuel did not correlate at all with the laboratory values obtained. This is not surprising since the moisture meter is not expected to give accurate readings (biased low) for a moisture content greater than 30%. However, for the last set of QA samples taken, 8/31-9/15/81, the laboratory procedure yielded higher moisture values than the meter even when the meter measurement was less than 30%. For the last three samples, the meter readings were 23, 25, and 19 percent, while the laboratory values were 40, 45, and 28 percent, respectively. On the last two samples, only a single center cross-section was taken; this might account for part of the discrepency. One possible explanation is that these samples may have been taken from the second lot of wood which was not totally cured; a portion of the laboratory weight loss measured as moisture might have actually been volatile organics. Nonetheless, with the exception of the high moisture values, the meter measurements were used as the fuel moisture content.

PARTICULATE SAMPLING

Particulate sample collection was conducted according to Reference Method 5 procedures with the exception that single point sampling was conducted. Prior to testing, the gas and orifice meters were calibrated according to standard procedures (calibration data in Appendix C). The pitot tubes also were calibrated. As per Method 5, reagent and filter blanks were taken and analyzed along with the samples.

No irregularities were encountered, with the exception of the velocity measurements, which already have been discussed.

GASEOUS MEASUREMENTS

Carbon monoxide, carbon dioxide, oxygen and hydrocarbon cylinder gases were procured and utilized for calibrating all gaseous measurement instruments. One gas cylinder for each compound (except HC) was obtained from the EPA quality assurance laboratory in order to provide an independent audit. The NDIR and Oxygen meter were calibrated prior to and immediately following each days testing. A three point CO and CO_2 calibration was conducted; two point calibrations for oxygen and hydrocarbons were conducted. The calibration gases available and the daily calibrations followed are summarized in Table 52 .

Orsat calibrations generally were conducted at only a single point. Problems were encountered with CO and orsat measurements during the test period. The CO adsorbing solution was changed during the test program (7/23/81); on 9/03/81 orsat instruments were switched due to problems with CO adsorption.

TABLE 52

Calibration Gases

Carbon Monoxide (percent)	Daily Calibration
0 (ambient)	
0.260*	
0.501	✓
7.25	✓
Carbon Dioxide (percent)	
3.57*	✓
7.47	✓
13.0	
Oxygen (percent)	
3.70*	
20.9 (ambient)	✓
Hydrocarbon (ppm)	
0 (ambient)	✓
710	✓

* EPA certified cylinder gas

TRANSMISSOMETER

The transmissometer system was constructed according to the specifications for the Smoke Generator Transmissometer System of EPA Reference Method 9 -- Visual Determination of Opacity of Emissions from Stationary Sources. Construction details are provided in the Appendix.

Prior to testing the instrument, linearity was checked using a three point calibration with neutral density filters. The filters used were 195., 50.1, and 79.4 percent transmission. These filters were used to check instrument calibration prior to each test. Calibration was not checked after each test due to the fact that residual (low level) emissions generally continued after the testing ended. A series of certified neutral density filters were obtained from the Quality Assurance Division of EPA and were used to audit the calibration. This audit indicated the instrument was properly calibrated. The results of the initial and final calibration, as well as the audit calibration are reported in Appendix C. The daily calibrations are not tabulated, but are noted on the permanent strip chart record.

Although the instrument indicated proper lineraity throughout the testing, some problems with upscale zero drift were encountered. This was indicated by the instrument not returning to baseline after the end of the test. However, it must be noted that the transmissometer is more sensitive than the visual observer and consequently, a visual observation of zero might be expected to indicate at least a 5% instrument reading. Consequently, it is probably not accurate to assume the final instrument reading is totally attributable to drift. Nonetheless, it appears more drift (5%) than should be tolerated (1-2%) was occurring. Significant drift (+10%) was noted for Run 2 and possibly Run 7. This normally would be caused by a change in output of the power source, or in alignment problems caused by expansion and contraction of the stack due to temperature extremes. On 8/27/81 prior to Run 12, the power source was changed. This seems to have significantly improved the drift problem. At the end of Run 12, the instrument and observer compare favorably (5-10%); the next morning without recalibration, the instrument calibrated accurately after having operated overnight (strip chart in Appendix C).

DATA REDUCTION

All calculations were conducted on a programmable calculator. Each program was independently checked (i.e., equations checked and at least one run compared to value calculated without program). A random audit of all calculations also was conducted.

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